



**QUEEN'S  
UNIVERSITY  
BELFAST**

## **Solar system science with the Wide-Field InfraRed Survey Telescope (WFIRST)**

Holler, B. J., Milam, S. N., Bauer, J. M., Alcock, C., Bannister, M. T., Bjoraker, G. L., Bodewits, D., Bosh, A. S., Buie, M. W., Farnham, T. L., Haghighipour, N., Hardersen, P. S., Harris, A. W., Hirata, C. M., Hsieh, H. H., Kelley, M. S. P., Knight, M. M., Kramer, E. A., Longobardo, A., ... West, R. A. (2017). Solar system science with the Wide-Field InfraRed Survey Telescope (WFIRST). *Proceedings of SPIE*.

**Published in:**  
Proceedings of SPIE

**Document Version:**  
Peer reviewed version

**Queen's University Belfast - Research Portal:**  
[Link to publication record in Queen's University Belfast Research Portal](#)

**Publisher rights**  
Copyright © 2018 SPIE. This work is made available online in accordance with the publisher's policies. Please refer to any applicable terms of use of the publisher.

**General rights**  
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**  
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact [openaccess@qub.ac.uk](mailto:openaccess@qub.ac.uk).

# Solar system science with the Wide-Field InfraRed Survey Telescope (WFIRST)

B.J. Holler<sup>1\*</sup>, S.N. Milam<sup>2\*</sup>, J.M. Bauer<sup>3,4\*</sup>, C. Alcock<sup>5</sup>, M.T. Bannister<sup>6</sup>, G.L. Bjoraker<sup>2</sup>, D. Bodewits<sup>3</sup>, A.S. Bosh<sup>7</sup>, M.W. Buie<sup>8</sup>, T.L. Farnham<sup>3</sup>, N. Haghighipour<sup>9</sup>, P.S. Hardersen<sup>10</sup>, A.W. Harris<sup>11</sup>, C.M. Hirata<sup>12</sup>, H.H. Hsieh<sup>13,14</sup>, M.S.P. Kelley<sup>3</sup>, M.M. Knight<sup>3</sup>, E.A. Kramer<sup>4</sup>, A. Longobardo<sup>15</sup>, C.A. Nixon<sup>2</sup>, E. Palomba<sup>15</sup>, S. Protopapa<sup>3</sup>, L.C. Quick<sup>16</sup>, D. Ragozzine<sup>17</sup>, V. Reddy<sup>18</sup>, J.D. Rhodes<sup>4</sup>, A.S. Rivkin<sup>19</sup>, G. Sarid<sup>20</sup>, A.A. Sickafoose<sup>21,7</sup>, A.A. Simon<sup>2</sup>, C.A. Thomas<sup>13</sup>, D.E. Trilling<sup>22</sup>, R.A. West<sup>4</sup>

<sup>1</sup>Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

<sup>2</sup>NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA

<sup>3</sup>Department of Astronomy, University of Maryland, College Park, MD 20742, USA

<sup>4</sup>Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

<sup>5</sup>Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

<sup>6</sup>Astrophysics Research Centre, Queen's University Belfast, Belfast BT7 1NN, UK

<sup>7</sup>Department of Earth, Atmospheric, and Planetary Sciences, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

<sup>8</sup>Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA

<sup>9</sup>Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI 96822, USA

<sup>10</sup>University of North Dakota, Department of Space Studies, 4149 University Avenue, Stop 9008, 530 Clifford Hall, Grand Forks, ND 58202, USA

<sup>11</sup>MoreData! Inc., 4603 Orange Knoll Avenue, La Cañada, CA 91011, USA

<sup>12</sup>Center for Cosmology and Astro Particle Physics (CCAPP), The Ohio State University, 191 West Woodruff Lane, Columbus, OH 43210, USA

<sup>13</sup>Planetary Science Institute, 1700 East Fort Lowell Road, Suite 106, Tucson, AZ 85719, USA

<sup>14</sup>Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan

<sup>15</sup>INAF Istituto di Astrofisica e Planetologia Spaziali, via Fosso del Cavaliere 100, Rome, Italy

<sup>16</sup>Smithsonian Institution, National Air and Space Museum, Center for Earth and Planetary Studies, Independence Avenue at 6<sup>th</sup> Street, SW, Washington, DC, 20560, USA

<sup>17</sup>Department of Physics and Astronomy, Brigham Young University, N283 ESC, Provo, UT 84602, USA

<sup>18</sup>Lunar and Planetary Laboratory, University of Arizona, 1629 E University Boulevard, Tucson, AZ 85721, USA

<sup>19</sup>Johns Hopkins University Applied Physics Laboratory, 11101 Johns Hopkins Road, Laurel, MD 20723, USA

<sup>20</sup>Florida Space Institute, University of Central Florida, 12354 Research Parkway, Orlando, FL 32826, USA

<sup>21</sup>South African Astronomical Observatory, P.O. Box 9, 7935 Observatory, Cape Town, South Africa

<sup>22</sup>Department of Physics and Astronomy, Northern Arizona University, P.O. Box 6010, Flagstaff, AZ 86011, USA

## **Abstract**

We present a community-led assessment of the capabilities of NASA's Wide Field InfraRed Survey Telescope (WFIRST) for solar system science. WFIRST will provide imaging and spectroscopic capabilities from 0.6-2.0  $\mu\text{m}$  and will be a potential contemporary and eventual successor to JWST. Observations of asteroids, the giant planets and their satellites, Kuiper Belt Objects, and comets will be possible through both the Guest Investigator (GI) and Guest Observer (GO) programs. Surveys of irregular satellites and minor bodies, as well as time domain studies of variable surfaces and atmospheres, are well-suited for WFIRST with its 0.28 deg<sup>2</sup> field of view. Potential ground-breaking WFIRST investigations include detection of the first minor bodies

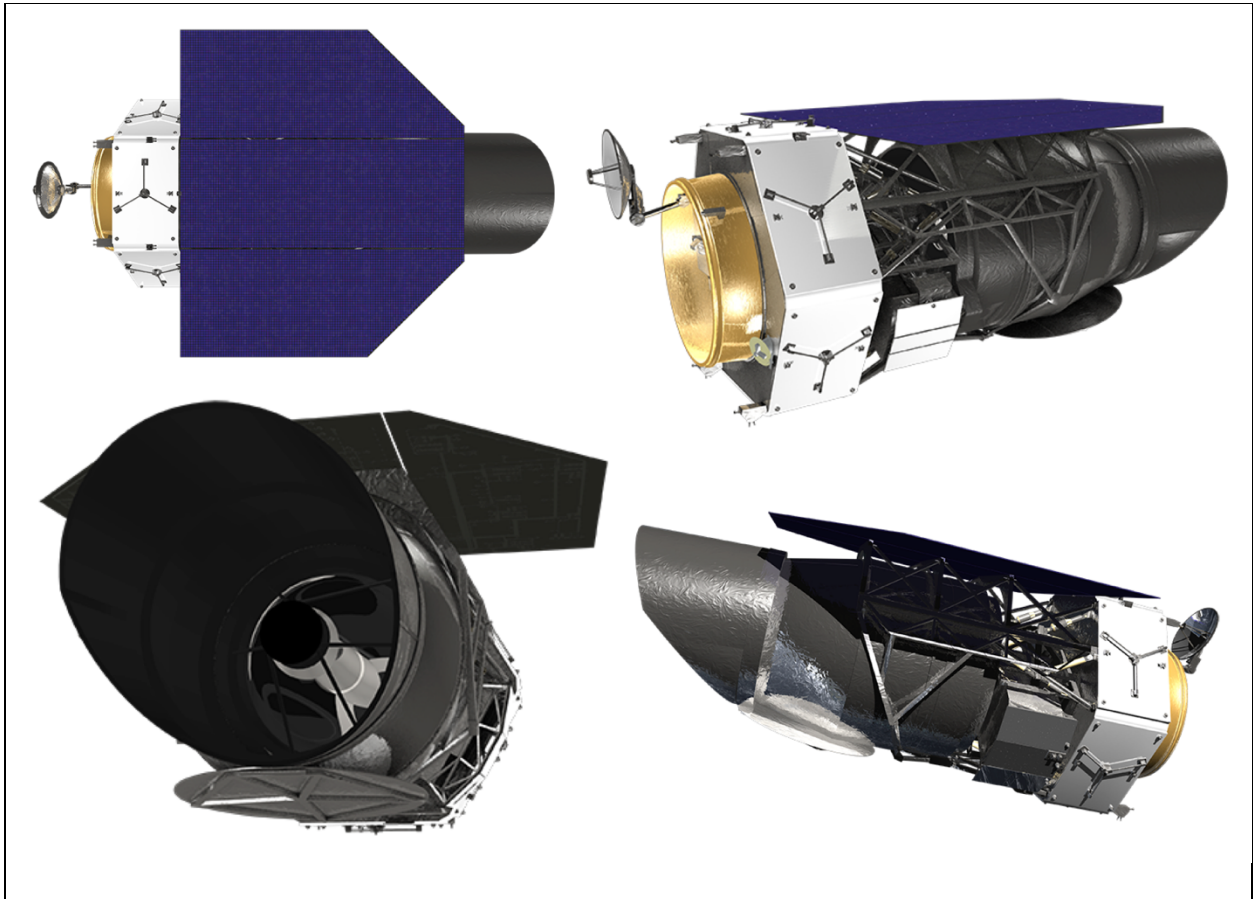
---

\* Corresponding authors: B.J. Holler (bholler@stsci.edu), S.N. Milam (stefanie.n.milam@nasa.gov), J.M. Bauer (gerbsb@umd.edu).

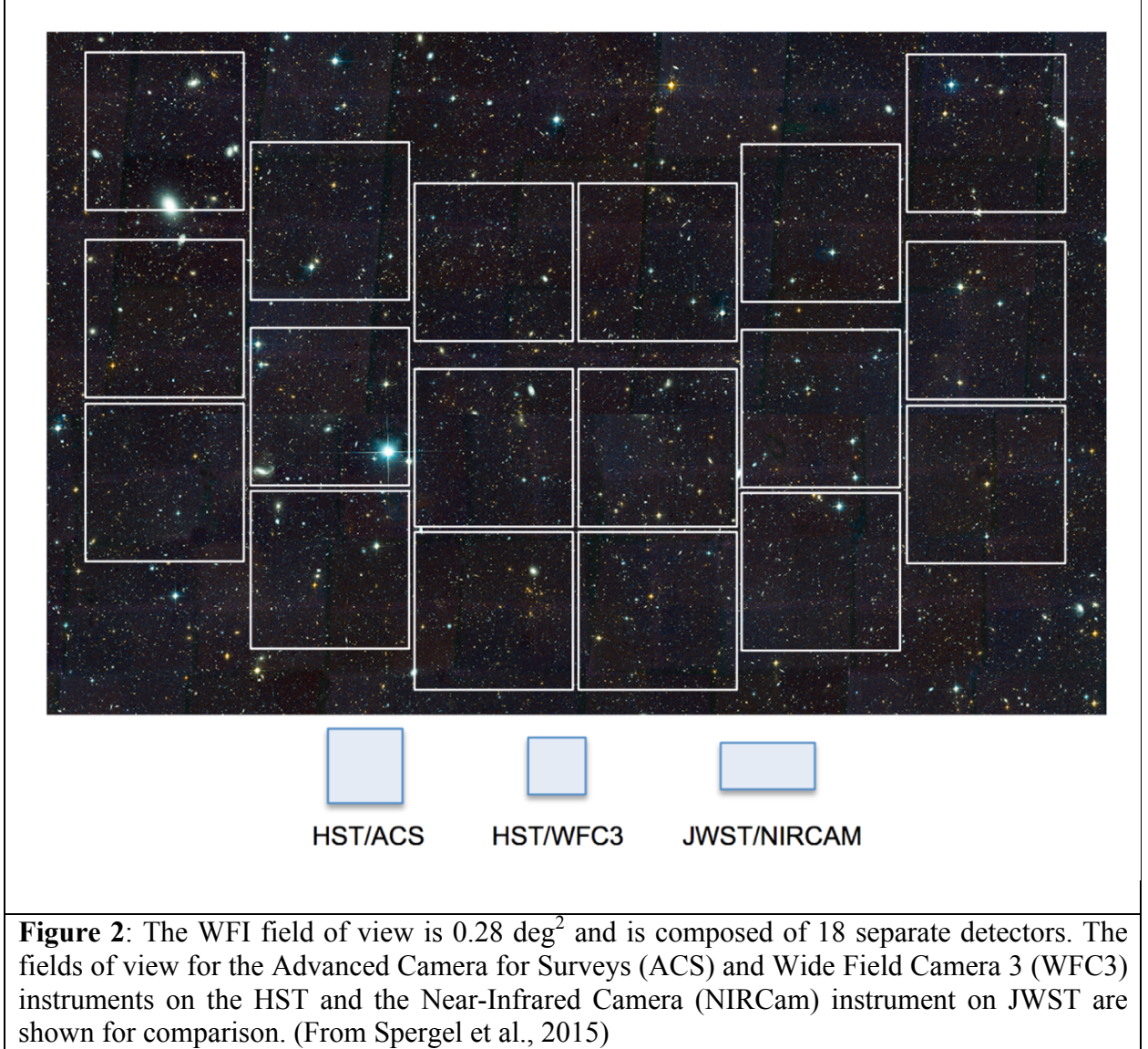
orbiting in the Inner Oort Cloud, identification of additional Earth Trojan asteroids, and the discovery and characterization of asteroid binary systems similar to Ida/Dactyl. Previous use of astrophysics assets for solar system science and synergies between WFIRST, LSST, JWST, and the proposed NEOCam mission are discussed. We also provide a list of proposed minor modifications to the mission, including non-sidereal tracking of 30 mas/s and a K-band filter ( $\sim 2.0\text{--}2.4\ \mu\text{m}$ ).

## **1. Introduction**

The Wide Field InfraRed Survey Telescope (WFIRST) is NASA's next flagship space observatory after the James Webb Space Telescope (JWST). WFIRST will have a 2.4-meter primary mirror, equivalent to the Hubble Space Telescope's (HST) primary mirror, and is on track to launch in 2025 or 2026, with a 6-year nominal mission. This telescope (Fig. 1) will have two instruments onboard: The Wide Field Instrument (WFI) with a  $0.28\ \text{deg}^2$  FOV (Fig. 2), which includes the Integral Field Channel (IFC) that will obtain spectral information over the entirety of its FOV, and the Coronagraphic Instrument (CGI) that is designed to take images and spectra of super-Earths. Between these two instruments, WFIRST will be capable of imaging, grism spectroscopy, and R $\sim$ 100 imaging spectroscopy over the near-infrared wavelength range  $0.6\text{--}2.0\ \mu\text{m}$ . For solar system observations, the primary modes will be imaging and R $\sim$ 100 spectroscopy; grism spectroscopy will not be discussed further.



**Figure 1:** Four computer-generated models of the WFIRST spacecraft from different angles. The primary mirror is 2.4 meters in diameter, comparable to the primary mirror on the Hubble Space Telescope. WFIRST will orbit around the Earth-Sun L2 point located  $\sim 1.5$  million km from Earth (Spergel et al., 2015). (From wfirst.gsfc.nasa.gov)



**Figure 2:** The WFI field of view is  $0.28 \text{ deg}^2$  and is composed of 18 separate detectors. The fields of view for the Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) instruments on the HST and the Near-Infrared Camera (NIRCam) instrument on JWST are shown for comparison. (From Spergel et al., 2015)

WFIRST will operate at the Earth-Sun L2 point and its primary goal will be to carry out the following science programs: (1) an exoplanet microlensing survey near the galactic bulge, (2) CGI observations, (3) imaging and grism spectroscopy of galaxies at high galactic latitude, (4) a supernova survey with 3 different imaging depths and a spectroscopy component, and (5) Guest Observer (GO) science. Funding for the analysis of survey data outside the defined science teams will be part of the Guest Investigator (GI) program. GO programs are expected to comprise  $\sim 1.5$  years, or approximately 25%, of the nominal mission duration.

The imaging and spectroscopic capabilities of WFIRST (Gehrels et al., 2015; Spergel et al., 2015) are well-suited for studies of solar system objects. In particular, the wavelength range



(0.6-2.0  $\mu\text{m}$ ) of the IFC and the WFI covers diagnostic absorption features due to gases in the atmospheres of the giant planets and Titan, as well as ices on the surfaces of Europa, giant planet satellites, Centaurs, and Kuiper Belt Objects (KBOs). The IFC provides spectral information over its entire FOV (3.0"×3.15", 0.05" or 0.10"/pixel plate scale), enabling analysis of cloud compositions in the atmospheres of the giant planets, regional surface composition on Europa and Titan, and identification of volcanic activity on Io, to name a few potential investigations. The WFI will make observations through broadband filters (Table 1) at a plate scale of  $\sim 0.11$  "/pixel. (The R062 was announced following the development of the science cases and was therefore not considered in-depth in this paper. The wavelength range considered in this paper is 0.6-2.0  $\mu\text{m}$  for the WFI; the actual wavelength range is 0.48-2.0  $\mu\text{m}$ .) Broadband colors, to first order, are indicative of surface and atmospheric composition, and can be used to compare various minor body populations to each other to determine their origin and evolution over solar system history. Significant improvements to the characterization of the surfaces and atmospheres of solar system objects would be made possible by the inclusion of a K-band filter ( $\sim 2.0$ -2.4  $\mu\text{m}$ ) in the WFIRST filter wheel (see §6.2).

The primary WFIRST instruments for solar system science are the WFI and the IFC, but observations should also be possible with the CGI. The CGI is a coronagraph designed for imaging and spectroscopy of exoplanets with a contrast of  $10^{-9}$  ( $\Delta m=9$ ). The CGI covers 0.43 to 0.98  $\mu\text{m}$  and has an inner working angle of  $\sim 0.15$ ". The field of view is 10"x10" and the pixel scale is 0.0208"/pixel at 0.48  $\mu\text{m}$ . By blocking the bright central object, the CGI could be used for the study of satellites around main belt asteroids (§4.3.1) and detection of activity around active asteroids (§4.3.3) and Centaurs (§4.3.5). Due to the small inner working angle, observations of the ring systems of Uranus and Neptune (angular diameters of 3.7" and 2.3", respectively) would likely not be useful, since only a small fraction of the disks of these planets would be blocked.

**Table 1. WFI filter specifications (From Spergel et al., 2015)**

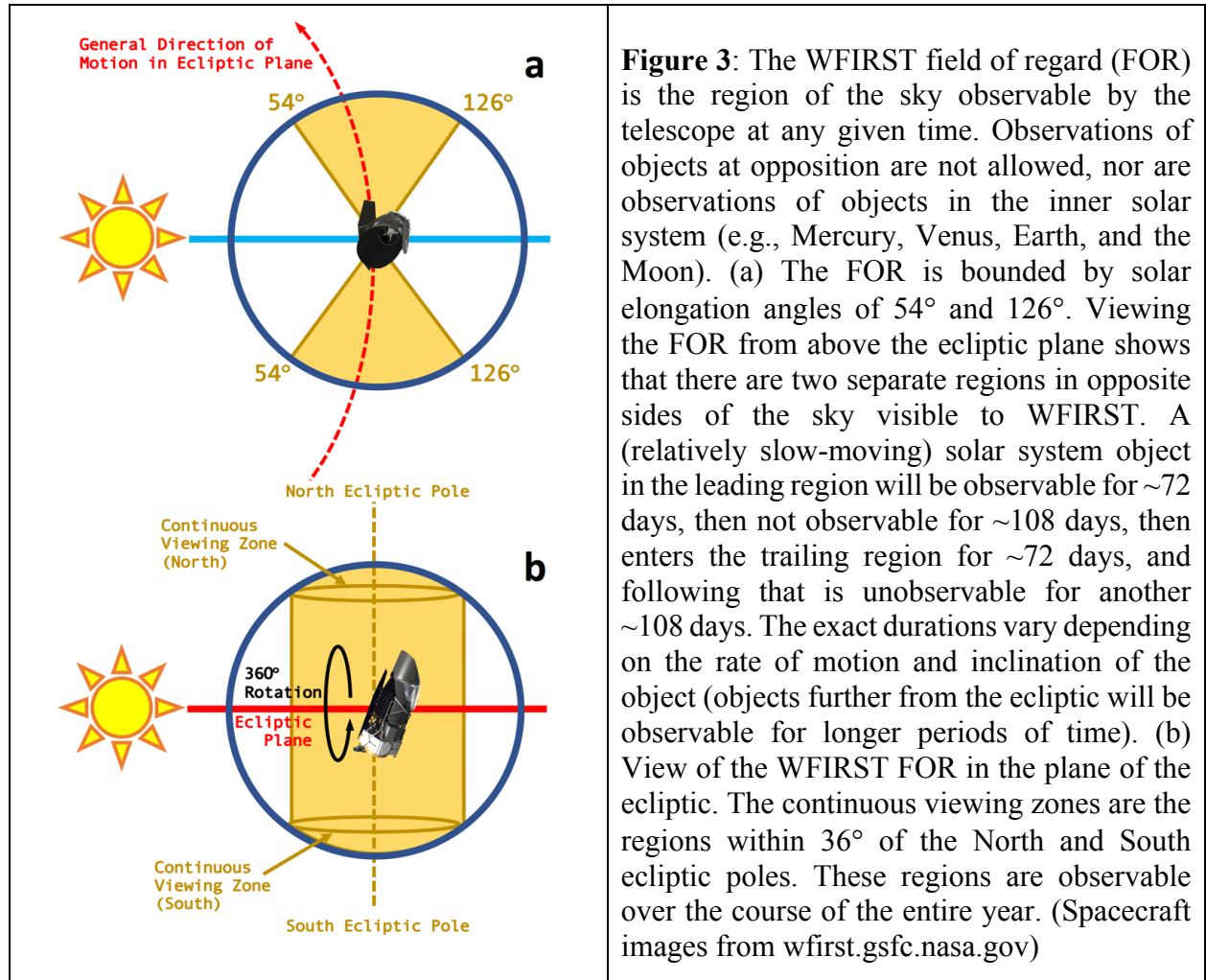
Filter	Bandpass ( $\mu\text{m}$ )	Center ( $\mu\text{m}$ )	Width ( $\mu\text{m}$ )
R062	0.480-0.760	0.620	0.280
Z087	0.760-0.927	0.869	0.217
Y106	0.927-1.192	1.060	0.265
J129	1.131-1.454	1.293	0.323
H158	1.380-1.774	1.577	0.394
F184	1.683-2.000	1.842	0.317
W149	0.927-2.000	1.485	1.030

The wide FOV of the WFI (0.28 deg<sup>2</sup>) will revolutionize targeted surveys. Large regions of the sky that typically required many pointings will be observable in one pointing with WFIRST. Exploration of the entirety of the Hill spheres surrounding the giant planets could add to the population of irregular satellites already known around these planets. The efficiency of surveys aimed at identifying new minor bodies would increase. Serendipitous occultations utilizing the rapid cadence of guide star imaging may yield more occultation candidates because each of the 18 detectors of the WFI has the ability to obtain its own guide star. All of these potential investigations, and others, are discussed in more detail in §4 and §5.

However, as with any ground- or space-based telescope, there are limitations to WFIRST's ability to observe solar system targets. A major limitation is the field of regard (FOR). WFIRST's solar panels act both to power the spacecraft and shield the telescope and instruments from solar

radiation. Thus, certain orientations with respect to the Sun are not allowed and only regions of the sky between solar elongation (Sun-WFIRST-target) angles of  $54^\circ$  and  $126^\circ$  will be observable at any given time (Fig. 3). This means that objects at opposition are unobservable. Additionally, inner solar system objects such as the Sun, Mercury, Venus, Earth, the Moon, and some Near-Earth Asteroids (NEAs) and comets will be unobservable. A further limitation is the assumed 30 milliarcsecond/second (mas/s) speed limit on non-sidereal tracking (this is the maximum non-sidereal track rate for JWST; e.g., Milam et al., 2016). For WFIRST, this affects the NEAs and long-period comets (§4.3.7), with  $\sim 10\%$  of NEAs and  $>50\%$  of long-period comets unobservable when in the FOR. A further discussion of non-sidereal tracking, and how solar system science with WFIRST would be impossible without it, can be found in §6.1.

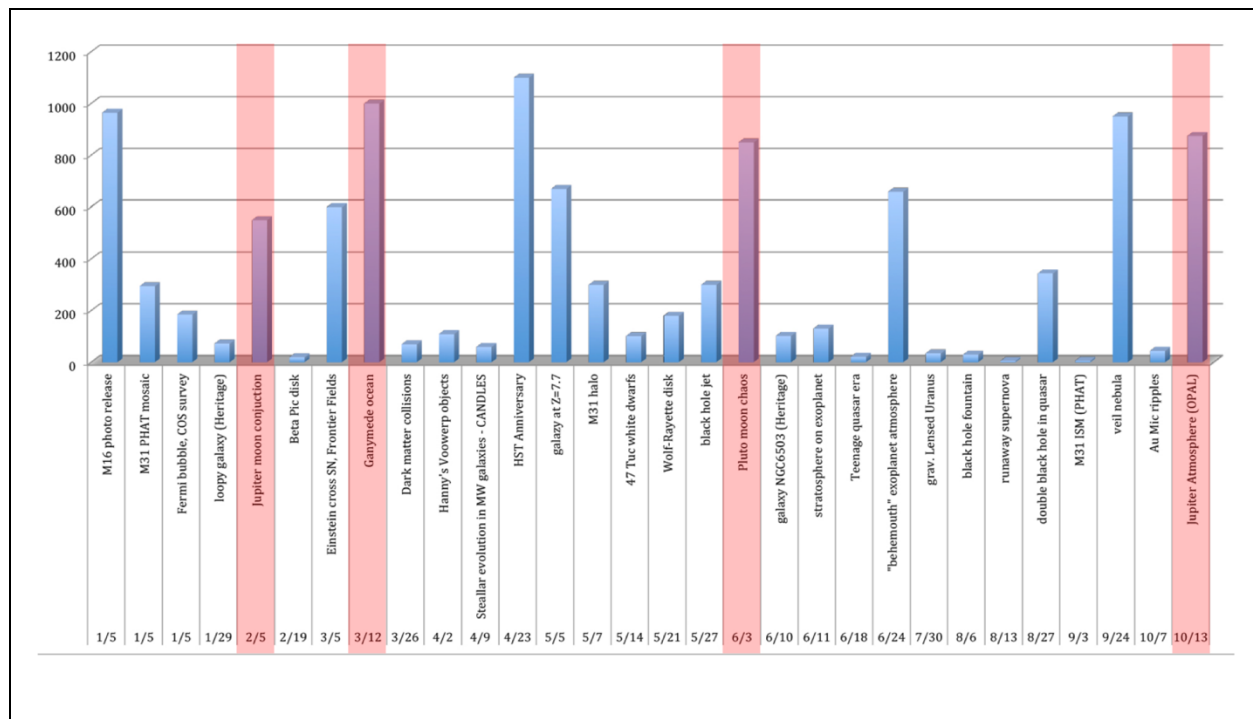
Despite the aforementioned limitations, WFIRST is poised to make meaningful contributions to the study of the solar system, and the goal of this paper is to present the community's vision and how it can be realized. In the following sections, we discuss the successful use of past and present astrophysics assets for solar system science (§2), the formation and work of the WFIRST Solar System Working Group (§3), potential GO programs (§4), potential GI programs (§5), describe low-risk, high-reward augmentations to the mission that would allow the solar system science community to make the best use of WFIRST (§6), and encourage the community to stay up-to-date with the development of WFIRST (§7).



## 2. Solar system science with astrophysics assets

### 2.1. Public interest in Solar System science

WFIRST, in the tradition of other NASA astrophysics assets, is primed to deliver observations of solar system objects that will not only contribute to the advancement of the field, but also excite the public. As seen in Figure 4, press releases on solar system observations with HST attract a proportionally larger share of the total circulation compared to the number of press releases. solar system observations therefore contribute in a significant way to the public profile of a space telescope mission, while only accounting for a small percentage of the total observing time (over the lifetime of HST this is around 4% of the total requested time).



**Figure 4:** Hubble Space Telescope (HST) press releases from 2015; the y-axis is circulation in millions. Solar system science accounts for a disproportionately large fraction of the circulation (and therefore public outreach) compared to the time granted to solar system observing programs. In total, 4 of 30 HST press releases were made on solar system science in 2015 (highlighted in red), of which 3 of those had a circulation above 800 million, accounting for half of the number of press releases above that mark. The story on Ganymede's ocean reached a circulation of almost 1 billion and was second only to the 25<sup>th</sup> anniversary of HST. (Source: Meltwater News Service)

### 2.2. Previous use of astrophysics assets

The past quarter century has seen an increase in the number of astrophysics assets located in space. Furthermore, there is an ongoing shift from locating these facilities in low-Earth orbit to the Earth-Sun L2 point. This is due to the need to place these infrared facilities in a stable thermal environment away from the thermal pollution that pervades the near-Earth region and is indicative of the desire in many fields of astronomy for observations at longer wavelengths. Solar system

studies is one such field, and will look to use WFIRST in the same manner as the other astrophysics assets before it.

The most successful of these previous astrophysics assets, both in terms of longevity and output, is the Hubble Space Telescope. HST has made significant contributions to our understanding of the solar system, from the atmosphere of Venus to the surface compositions of KBOs, but one area in which HST has really excelled is the detection of new satellites, especially in the outer solar system. These discoveries include two new classical Uranian satellites (Showalter and Lissauer, 2006), one new classical Neptunian satellite (Showalter et al., 2013), a hierarchical triple system in the Kuiper Belt (Benecchi et al., 2010), and the recent detection of a satellite around each of the dwarf planet-class objects Makemake (Parker et al., 2016) and 2007 OR<sub>10</sub> (Kiss et al., 2017). In the case of the ice giants, these new, small satellites paint a more complicated picture of satellite origins and evolution: The small Uranian satellites point to a dynamic picture of moon-ring interactions, while the new Neptunian satellite provides evidence that the capture of Triton resulted in the destruction of the original inner satellites and accretion of the current satellites (Agnor and Hamilton, 2006). For the KBOs, calculating the orbit of a satellite provides an estimate of the system mass, which tends to be dominated by the primary. The total mass of the Kuiper Belt is currently not well-constrained because the size distribution and binary fraction of KBOs are only poorly understood. The mass of the current Kuiper Belt is important for comparison to the predicted mass of the primordial Kuiper Belt: How much material was lost from the solar system or captured into other minor body populations? WFIRST will be able to contribute to this topic, both through detection and characterization of more KBO binary systems and colorimetry of other minor body populations (§5.2).

Some of these satellite detections were made in the Pluto system. Of Pluto's 5 satellites, only one, Charon, was discovered using a different facility (Christy and Harrington, 1978). The 4 minor satellites, Styx, Nix, Kerberos, and Hydra, were all discovered in deep images from HST (Weaver et al., 2006; Showalter et al., 2011, 2012). Other important discoveries in the Pluto system were made with HST, including valuable pre-flyby context for NASA's New Horizons mission through the creation of surface maps of Pluto and Charon (Buie et al., 2010) and the discovery of the chaotic rotation of the minor satellites (Showalter and Hamilton, 2015). The target of the New Horizons extended mission, 2014 MU<sub>69</sub>, was discovered using HST (Spencer et al., 2015).

Astrophysics assets have provided valuable support and follow-up for other planetary missions. NASA's Spitzer Space Telescope obtained mid-infrared spectra of the Deep Impact target, comet 9P/Tempel, shortly after the impactor hit the surface (Lisse et al., 2006). These spectra provided valuable information on the composition of the excavated material, and the chemical make-up of the comet as a whole. Spitzer was also responsible for the discovery of Saturn's largest, most diffuse ring, the Phoebe ring, that went undetected by the *in-situ* Cassini spacecraft (Verbiscer et al., 2009). But not all observations in support of a planetary mission have been simultaneous. HST provided long-term follow-up observations of images from Voyagers 1 and 2 of Titan and Triton, resulting in the detection of seasonal changes on both satellites (Caldwell et al., 1992; Bauer et al., 2010). (The Titan observations were made a few months after the launch of HST in 1990.) Other HST observations have provided context and momentum for future missions, such as Europa Clipper, with the recent detection of water ice plumes around Europa (Roth et al., 2014; Sparks et al., 2016). WFIRST is set to operate during some of these future missions and will therefore be able to provide simultaneous support observations, and possibly generate momentum for the next generation of planetary missions in the 2030s and 2040s.



Large observing programs with astrophysics assets have enabled the study of sizeable samples of minor body populations. Expansive, consistent data sets were produced with Spitzer, the Herschel Space Observatory, the Wide-field Infrared Survey Explorer (WISE), and the repurposed NEOWISE mission (an ongoing, as of mid-2017, extension to the WISE mission following the depletion of coolant; Mainzer et al., 2011, 2014). The “TNOs are Cool” Herschel program was a survey of KBOs at far-infrared wavelengths for the purpose of calculating diameters and albedos (Müller et al., 2009). At the time of this writing, 12 papers based on these data have been published. Two of those papers combined Spitzer and Herschel data to determine more of the thermal properties of Centaurs and KBOs (Lellouch et al., 2013; Vilenius et al., 2014). Spitzer also produced a consistent data set for the study of active comets, resulting in a new classification scheme for comets (Reach et al., 2013). WISE, and the later NEOWISE extension, were dedicated survey missions in the far-infrared that observed minor bodies from a wide variety of different populations, including ~100,000 main belt asteroids, 5 active asteroids, 163 comets, and 52 Centaurs and KBOs (Masiero et al., 2011; Bauer et al., 2012, 2013, 2015). As of July 10<sup>th</sup>, 2017, WISE was credited with the discovery of 12252 numbered minor bodies, including the first and only known Earth Trojan asteroid (Connors et al., 2011). Earth Trojans are difficult objects to detect from the surface of the Earth because they are, on average, directly overhead ~2 hours before sunset or after sunrise. Surveys with astrophysics assets can also operate in the time domain. An ongoing Hubble 2020 program, the Outer Planet Atmospheres Legacy (OPAL), will obtain complete maps of each of the giant planets once a year for every year that HST continues to operate in order to resolve long-term atmospheric changes, such as the evolution of storms in Jupiter’s atmosphere (Simon et al., 2015). The WFI, with its large FOV, will enable WFIRST to match or exceed these other missions in survey productivity by producing a large, consistent data set of minor bodies and irregular satellites in the near-infrared.

Some solar system observations made unexpected use of astrophysics assets or produced very surprising results. For instance, X-ray emission from Pluto was detected using the Chandra X-ray Observatory (Lisse et al., 2017). Active comets are known to produce X-rays, and have been observed with Chandra (Bodewits et al., 2007), but this detection at such a large distance from the Sun (~32 AU) remains a mystery. Also at a heliocentric distance of 32 AU, but at longer wavelengths, Herschel provided an albedo measurement of comet Hale-Bopp ~15 years after perihelion; the albedo was much higher than that of a typical comet, suggesting freeze-out of fresh material onto the comet nucleus (Szabó et al., 2012). Other novel investigations have been performed with the Ultraviolet/Optical Telescope (UVOT) on the Swift Gamma-Ray Burst mission, including a calculation of the rotation period of the dwarf planet Eris (Roe et al., 2008), observations of active asteroids (e.g., Bodewits et al., 2011), and observations of comet C/2013 A1 (Siding Spring) during its close approach to Mars (Bodewits et al., 2015). Sometimes unexpected opportunities present themselves, as is the case with the repurposed Kepler mission, now known as K2. Following the loss of half of the spacecraft’s reaction wheels in 2013 (necessary components for accurate pointing of the telescope) the mission was altered so that it could only observe fields along the ecliptic. This resulted in high-cadence time-domain observations of solar system objects such as the rotation light curves of Jupiter Trojans (Ryan et al., 2017; Szabó et al., 2017), the KBO 2007 OR<sub>10</sub> (Pál et al., 2016), the irregular satellites of Uranus (Farkas-Takács et al., 2017), and Neptune’s atmosphere (Simon et al., 2016). The slow rotation period observed for 2007 OR<sub>10</sub> led to a search for a satellite that was ultimately discovered in archival HST images (Kiss et al., 2017) and the Uranus field also yielded observations of over 600 main belt asteroids, including 86 new light curves (Molnár et al., 2017). The solar system community, drawing on

these previous experiences, is prepared to develop clever investigations and take advantage of unexpected opportunities with WFIRST.

### 2.3. Synergies with JWST and LSST

It is anticipated that both JWST and the Large Synoptic Survey Telescope (LSST) will be operational during at least a portion of WFIRST’s 6-year nominal mission beginning in 2025 or 2026. The goal for JWST is a 10-year mission beginning in Spring 2019, and therefore has the potential to operate in conjunction with WFIRST at L2 for up to 3-4 years. (JWST’s nominal mission is from 2019-2024, which would result in no overlap with WFIRST.) The plan for LSST is to begin its primary 10-year survey in 2022, resulting in simultaneous operations over the entirety of WFIRST’s nominal lifetime.

#### 2.3.1 JWST

WFIRST and JWST provide complementary, rather than overlapping, capabilities to each other. Though both will orbit around the Earth-Sun L2 point, the FOR of WFIRST is nearly 50% larger than that of JWST ( $54^{\circ}$ - $126^{\circ}$  compared to  $85^{\circ}$ - $135^{\circ}$ ). Assuming both will be operating at the same time, an object on the ecliptic will first be observable by WFIRST approximately one month prior to being observable by JWST. Then the object will be observable by both for  $\sim 1.5$  months, followed by 1-2 weeks when it is only observable by JWST. Then the process repeats in reverse for the trailing window. Together, WFIRST and JWST will be able to observe solar system objects along the ecliptic for nearly half of each year.

JWST has a larger primary mirror ( $\sim 7$  times the light gathering power), a broader wavelength range ( $0.6$ - $28.8 \mu\text{m}$ ), and a handful of different spectroscopy modes, while WFIRST’s major strength for solar system observations is its  $0.28 \text{ deg}^2$  FOV (Fig. 2). However, it is not useful to compare the two observatories in this manner because each is designed for different purposes, as evidenced by recently published JWST solar system science cases (an overview can be found in Milam et al., 2016) and the work presented here. The science cases for these two observatories are, again, complementary: the JWST cases typically focus on a handful of objects from important populations and are heavy on spectroscopy, while the WFIRST cases are directed more at surveys and larger sample sizes with its considerable imaging FOV (see §4 and §5).

During the potential period of simultaneous operations, the two observatories could work together to increase the science gains from both. Time-domain studies of variable objects, such as comets, can be “handed off” as the object passes through the FOR of each observatory, as discussed above. WFIRST is likely to identify more minor bodies than JWST, with the brighter objects being passed to JWST for spectral observations. With the proper orbital alignment, one could even imagine WFIRST and JWST setting up a mini “picket fence” around the L2 point for target of opportunity observations of a stellar occultation by a minor body. Many other interesting uses of WFIRST and JWST either in tandem or in sequence exist and may someday lead to extraordinary discoveries in our own solar system.

#### 2.3.2. LSST

The LSST is an 8.4-meter ground-based telescope currently under construction on Cerro Pachón in Chile (LSST Science Collaboration, 2009). Beginning in 2022, LSST will undertake a 10-year survey of the entire southern sky, and a small portion of the northern sky along the ecliptic, covering a total of approximately  $25,000 \text{ deg}^2$ . It is currently planned for the same area of sky to be observed every 3-4 days (the exact cadence is still open to community input). Covering such a

large area of sky in such a short time period requires (1) a large FOV and (2) short exposures. LSST accomplishes this with an FOV of  $9.6 \text{ deg}^2$ , or  $\sim 34$  times larger than the WFI FOV, and two 15-second exposures through one of the 6 available SDSS filters (*ugrizy*) at each sky position.

The proposed cadence of the LSST survey will provide a unique opportunity for the identification and study of minor bodies in the solar system, including improved orbit determinations, rotation light curves, and colorimetry. However, the downside to this fast cadence is that the individual observations themselves will not probe very deep. Identification of new, faint objects could be quickly followed-up with deeper observations by WFIRST, assuming an appropriate target of opportunity (ToO) program is in place. Such a ToO program should be capable of triggering within 1 week from the desired start time of the observations (depending on the object's apparent rate of motion) to prevent loss of the newly identified object. A further description of ToO triggering specifications is found in §6.4.

The SDSS filters on LSST will cover the near-UV to near-infrared range from  $0.32\text{--}1.05 \mu\text{m}$ , with WFIRST covering the near-infrared range from  $0.6\text{--}2.0 \mu\text{m}$ . The overlap between these two wavelength ranges provides a means of calibrating the data sets for full spectral photometry between the near-UV and the near-infrared.

Another important synergy between WFIRST and LSST is complementary sky coverage. A major detractor for both WFIRST and JWST is their inability to observe solar system objects at opposition, when they are at their brightest. This is especially important for faint minor bodies that may be more difficult to observe at other solar elongation angles, and for phase angle studies. LSST potentially fills that gap by providing coverage for objects at opposition, as long as they are observable in the southern half of the sky. A WFIRST ToO program could provide follow-up for tracking newly identified objects that pass out of the LSST survey region but that remain within the WFIRST FOR.

An interesting prospect with LSST is the identification of dwarf planet-class Kuiper Belt Objects (KBOs) passing through the galactic plane. These regions are typically avoided in targeted surveys and a  $\sim 1000\text{-km}$  diameter KBO could conceivably be detected in 30 seconds of imaging with LSST; this assumes adequate subtraction of field stars in the LSST pipeline. Due to large orbital uncertainties shortly after detection, the  $0.28 \text{ deg}^2$  FOV of the WFI would have no issues acquiring the object for the necessary follow-up observations. Such observations would include deeper imaging to gain a better understanding of the physical properties of the KBO, while simultaneously providing the information for an improved orbital solution. WFIRST could also provide spectral follow-up with the IFC since LSST will have no spectral capabilities.

## **2.4. Planetary mission support**

NASA is currently developing a handful of new planetary missions in the Discovery and Flagship categories that will be operational in the 2020s and beyond. These missions are in various stages of development, and WFIRST will be able to provide support in different forms for most, if not all, of them. Missions planned for the 2030s would benefit from observations for the purpose of defining science goals; WFIRST would provide complementary observations to those of concurrent missions; and for those nearing the end of their nominal missions, WFIRST could provide valuable information for guiding extended missions. A perfect example of a NASA astrophysics asset supporting a planetary mission was the discovery of the New Horizons extended mission target, 2014 MU<sub>69</sub>, by HST (Spencer et al., 2015). WFIRST's deep imaging capability may someday do the same for a future, as yet unplanned, flyby mission.

WFIRST will be in a position to provide valuable context for the results of the Discovery-class mission Lucy, planned to launch in 2021. From 2025 to 2033, Lucy will encounter 1 main belt asteroid and 5 Jupiter Trojans (Levison et al., 2017). The Trojan targets include 3548 Eurybates, the largest member of a collisional family of Trojan asteroids; 11351 Leucus, an object with a rotation period potentially greater than 500 hours (French et al., 2013); and 617 Patroclus, a binary Trojan with components of roughly equal size. Observations with WFIRST would place the flyby results in context through further study of the Trojan population as a whole (§4.3.4). WFIRST could contribute to our understanding of the origins of these minor bodies, identify more collisional families through improved orbital solutions and colorimetry, identify new binaries, and measure rotation periods for a larger sample of Trojans.

Continuing with NASA missions to study minor bodies, WFIRST may provide complementary observations to that of the Near-Earth Object Camera (NEOCam). NEOCam was not officially selected in the previous round of Discovery-class missions, but was provided with an additional year of funding to explore possibilities for future implementation. NEOCam was designed specifically to identify and characterize a larger number of currently unknown potentially hazardous asteroids (PHAs), and has the capability to measure the diameters and thermal inertias of these objects (Mainzer et al., 2015). As originally designed, NEOCam images at longer near-infrared wavelengths from 4-5  $\mu\text{m}$  and 6-10  $\mu\text{m}$ . Simultaneous surveys by LSST, WFIRST, and NEOCam would therefore cover a very large region of the sky from the visible through to the end of the near-infrared. NEOCam would also be able to observe objects moving at very high apparent rates that cannot be tracked by WFIRST. The combination of LSST's fast cadence, WFIRST's field of view, and NEOCam's tracking capability would potentially result in a complete catalog of PHAs that could threaten life on Earth.

WFIRST would also provide useful observations in support of NASA Flagship missions, like the Europa Clipper (Pappalardo et al., 2015). Set to launch in the early 2020s and arrive at Jupiter in the mid-2020s, the purpose of this mission is to study the potential habitability of Europa's sub-surface ocean through compositional and geologic analysis. Europa Clipper will orbit Jupiter and make multiple flybys over the surface of Europa. WFIRST will be able to provide support for these science goals through time-domain, longitudinal studies of Europa's surface composition. WFIRST may be able to indirectly identify locations of recent or ongoing plume activity on Europa through spatially-resolved spectroscopy of the surface with the IFC: regions with recent activity will be rich in salts and have weaker water ice absorption (§4.2.1.2). Longitudinal coverage over a large time baseline would help to identify regions of interest for Europa Clipper to focus on during its flybys over Europa's surface.

The planets Uranus and Neptune have not been visited by spacecraft since Voyager 2 flew by them in 1986 and 1989, respectively. This was recognized in the 2013-2022 Decadal Survey, prompting the development of a science definition team and a report on possible Flagship missions to visit one of these giant planets. Flight paths and science goals were identified for a Flagship mission to each planet. A mission to Uranus would launch between 2030-2034 and arrive between 2041-2045; a mission to Neptune would launch between 2029-2030 and arrive between 2042-2043. Two identified science objectives, for which WFIRST could provide a contribution, are to study atmospheric winds and storms (lifecycle and seasonal timing) and take an inventory of smaller satellites. Images and near-infrared spectra of the atmospheres of Uranus and Neptune (§4.1.2) will be obtainable with the WFI and IFC, respectively, enabling the study of winds, clouds, and potential storms during seasonal transitions. WFIRST's wide field of view will provide deep imaging of the Hill spheres of these giant planets in only a handful of separate pointings, thus



contributing to the inventory of irregular satellites (§4.2.2). By the time the WFIRST mission begins, the target, Uranus or Neptune, will have been chosen for the Flagship mission, so the aforementioned observations will help guide the specific science objectives and flight paths of each mission. For example, an extended time-baseline of atmospheric events provided by WFIRST would help put the results of the Flagship mission in context. Additionally, discovery and orbital characterization of a new irregular satellite (perhaps one that is a different color from other irregular satellites in the system) may prompt a flight path that takes the spacecraft on a close approach to the object, as was done with Cassini and Saturn’s irregular satellite, Phoebe.

### **3. WFIRST Solar System Working Group**

The WFIRST Solar System Working Group (SSWG) was formed in December 2016. Membership was advertised to the solar system science community through an open call for volunteers. Presently, its members span the range of solar system expertise, including the many minor body populations, giant planet atmospheres, satellite studies, and occultations. The SSWG members divided themselves into 7 sub-groups covering these topics: Asteroids/NEOs/PHAs, Giant Planets, Satellites, Triton, KBOs/TNOs/Centaurs/Binaries, Comets, and Occultations. Each sub-group was tasked with identifying the science capabilities of WFIRST, as well as key augmentations to facilitate an active planetary science program. In response, the sub-groups produced the science cases outlined in Table 2, and presented in more detail in the next sections. Tables 3 and 4 provide brightness estimates for a variety of solar system targets, some of which are explicitly discussed in this paper.

**Table 2. WFIRST Solar system science cases**

<b>Science case</b>	<b>Rate (mas/s)</b>	<b>Instrument(s)</b>	<b>GO/GI</b>
§4.1.1: Jupiter atmosphere	10	WFI/IFC	GO
§4.1.1: Saturn atmosphere	5.5	WFI/IFC	GO
§4.1.2: Uranus atmosphere	2.5	WFI/IFC	GO
§4.1.2: Neptune atmosphere	1.5	WFI/IFC	GO
§4.2.1.1: Io volcanoes	10	IFC	GO
§4.2.1.2: Europa plumes	10	IFC	GO
§4.2.1.3: Titan clouds	5.5	IFC	GO
§4.2.1.4: Smaller giant planet satellites	1.5-10	IFC	GO
§4.2.2: Irregular satellites	1.5-10	WFI	GO/GI
§4.3.1: Binary asteroids with the CGI	$\leq 40$	CGI	GO
§4.3.2: Asteroid families	$\leq 40$	IFC	GO/GI
§4.3.3: Active asteroids	$\leq 30$	WFI/IFC/CGI	GO/GI
§4.3.4: Jupiter Trojans	10	WFI/IFC	GO/GI
§4.3.5: Centaurs	1.5-10	WFI/IFC/CGI	GO/GI
§4.3.6: Kuiper Belt Objects (KBOs)	0.5-1.5	WFI/IFC	GO/GI
§4.3.7: Comets	$\leq 60$	WFI/IFC	GO/GI
§4.3.8: Inner Oort Cloud objects	$\leq 0.5$	WFI	GO/GI
§4.4.1: Targeted occultations	N/A	WFI	GO
§4.4.2: Serendipitous occultations	N/A	WFI/IFC	GI

**Table 3. Surface brightness estimates of extended Solar system targets**

Target	$p_v$	D (km)	r (AU)	$\Delta$ (AU)	1.5 $\mu\text{m}$ (Jy/ $\square''$ )
<i>Giant Planets</i>					
Jupiter	0.538	142984	5.09	4.45	29
Saturn	0.499	120536	9.53	8.92	7.7
Uranus	0.488	51118	19.51	18.90	1.8
Neptune	0.442	49528	29.89	29.29	0.69
<i>Large Satellites</i>					
Io	0.62	3643	5.09	4.45	34
Europa	0.68	3122	5.09	4.45	37
Ganymede	0.44	5262	5.09	4.45	24
Callisto	0.19	4821	5.09	4.45	10
Rhea	0.7	1527	9.53	8.92	11
Titan	0.22	5150	9.53	8.92	3.4
Iapetus (dark)	0.05	1470	9.53	8.92	0.77
Iapetus (bright)	0.5	1470	9.53	8.92	7.7
<i>Comet Example</i>					
Coma	N/A	N/A	3.0	2.5	0.19
<i>Main Belt Asteroids</i>					
1 Ceres	0.090	939	2.91	2.32	15
2 Pallas	0.101	545	3.39	2.70	12
4 Vesta	0.423	525	2.16	1.40	127
10 Hygiea	0.072	407	3.44	2.76	8.5

**Note.** Objects considered in this table are at least 2 WFI pixels in diameter and are therefore extended objects. For the Comet Example, we take the coma/nucleus brightness ratio be 250, with information on the Nucleus found in Table 4. The heliocentric (r) and observer ( $\Delta$ ) distances were obtained using JPL Horizons, with the observer at the Earth-Sun L2 point in 2025; the observer distance corresponds to the smallest value in 2025 when the object is in WFIRST’s field of regard. D is the diameter of the object and  $p_v$  is the visible geometric albedo. The flux density at 1.5  $\mu\text{m}$  ( $\lambda_0$  of the W149 filter), in Janskys, was calculated by considering the reflected solar flux and the emitted thermal flux from each object. The solid angle, in units of square arcseconds, was calculated as  $\pi(D/2\Delta)^2$ . We assume the solid angle of an extended comet coma is 0.20  $\square''$ .

**Table 4. Brightness estimates of compact Solar system targets**

Target	$p_v$	D (km)	r (AU)	$\Delta$ (AU)	1.5 $\mu\text{m}$ (mJy)
<i>Comet Example</i>					
Nucleus	0.04	10	3.0	2.5	0.15
<i>Asteroid Families</i>					
153 Hilda	0.062	171	4.17	3.50	18
434 Hungaria	0.726	8.9	1.84	1.04	33
8 Flora	0.226	147	2.36	1.63	692

298 Baptistina	0.131	21	2.09	1.35	15
44 Nysa	0.482	71	2.06	1.32	689
15 Eunomia	0.248	232	2.36	1.63	1892
<i>Jupiter Trojans</i>					
624 Hektor	0.025	225	5.15	4.51	4.9
617 Patroclus	0.047	180	4.67	4.01	9.1
<i>Saturnian Satellites</i>					
Mimas	0.6	396	9.53	8.92	27
Enceladus	1.0	504	9.53	8.92	74
Tethys	0.8	1062	9.53	8.92	262
Dione	0.7	1123	9.53	8.92	256
Hyperion	0.3	270	9.53	8.92	6.3
Phoebe	0.08	213	9.53	8.92	1.1
<i>Uranian Satellites</i>					
Miranda	0.32	472	19.51	18.90	1.1
Ariel	0.39	1158	19.51	18.90	8.1
Umbriel	0.21	1170	19.51	18.90	4.4
Titania	0.27	1578	19.51	18.90	10
Oberon	0.23	1522	19.51	18.90	8.2
Sycorax	0.04	150	19.51	18.90	0.014
<i>Neptunian Satellites</i>					
Triton	0.72	2707	29.89	29.29	14
Nereid	0.16	340	29.89	29.29	0.051
<i>Neptune Trojans</i>					
2013 KY <sub>18</sub>	0.08	200	29.04	28.43	0.0098
(316179) 2010 EN <sub>65</sub>	0.08	200	29.14	28.55	0.0097
<i>Centaur</i>					
(10199) Chariklo	0.045	302	17.53	16.91	0.098
(5145) Pholus	0.044	190	30.30	29.69	0.0041
(2060) Chiron	0.15	166	18.42	17.82	0.080
(60558) Echeclus	0.077	59	13.41	12.81	0.019
<i>Kuiper Belt Objects (KBOs)</i>					
(134340) Pluto	0.68	2374	35.27	34.67	5.4
Charon	0.31	1212	35.27	34.67	0.64
(136199) Eris	0.96	2274	95.53	94.94	0.13
(225088) 2007 OR <sub>10</sub>	0.089	1964	89.60	89.00	0.011
(136472) Makemake	0.81	1713	52.71	52.11	0.66
(136108) Haumea	0.804	1366	49.88	49.27	0.52

(50000) Quaoar	0.109	1347	42.64	42.03	0.13
(90377) Sedna	0.32	1190	83.09	82.50	0.020
(90482) Orcus	0.231	1014	48.01	47.41	0.098

**Note.** Objects considered in this table are comparable to or less than one WFI pixel in diameter and are therefore compact objects. Values for the Nucleus in the Comet Example are assumed. The diameter of 617 Patroclus is the effective diameter of the binary system, and the geometric albedo is the system albedo. The heliocentric ( $r$ ) and observer ( $\Delta$ ) distances were obtained using JPL Horizons, with the observer at the Earth-Sun L2 point in 2025; the observer distance corresponds to the smallest value in 2025 when the object is in WFIRST's field of regard.  $D$  is the diameter of the object and  $p_V$  is the visible geometric albedo. The flux density at  $1.5\ \mu\text{m}$  ( $\lambda_0$  of the W149 filter), in millijanskys, was calculated by considering the reflected solar flux and the emitted thermal flux from each object.

The science cases discussed in §4 were based on the baseline WFIRST mission, which includes the WFI, IFC, and CGI instruments, wavelength coverage from  $0.6\text{--}2.0\ \mu\text{m}$ , and moving target tracking. Recent budget overruns have led to a discussion about dropping the IFC and eliminating support for moving target tracking. A large fraction of our proposed science investigations would be negatively impacted by either or both of these proposed changes to the mission. Table 5 provides an impact assessment for each of the science cases when considering the removal of moving target tracking, the IFC, or both from the baseline mission. Only two investigations, detection of Inner Oort Cloud objects and occultations (both targeted and serendipitous), would be unaffected by the proposed changes; all other investigations would be negatively impacted, with most becoming impossible to carry out. We therefore stress the importance of both moving target tracking and the IFC for observations of solar system objects.

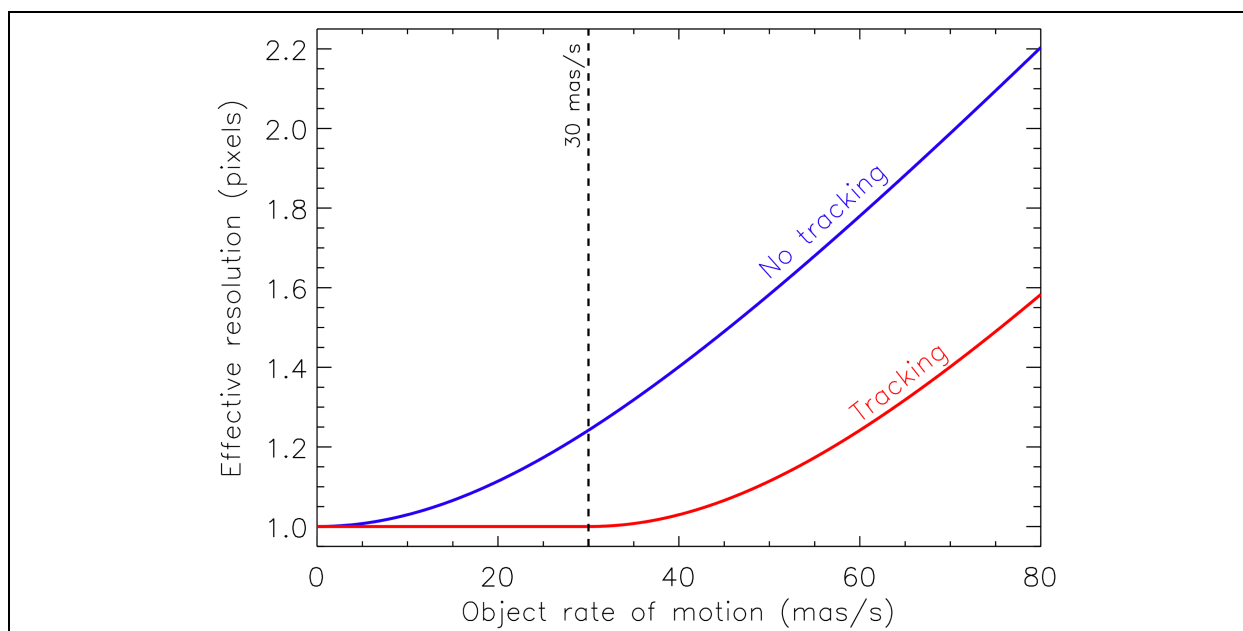
Solar system objects moving less than  $30\ \text{mas/s}$ , the nominal tracking rate based on the value for JWST, can be tracked exactly, without blurring the object on the detector. Objects moving faster than  $30\ \text{mas/s}$ , including near-Earth asteroids (NEAs) and long-period comets, can be tracked at the maximum rate, but will smear across the detector, even in the 2.7-second readout time for each individual WFI detector. Without moving target tracking, observations of all solar system objects, even the slowest moving objects in the Kuiper Belt, will be affected by blurring. Distribution of an object's flux over a larger number of pixels is not ideal, as this means more pixels must be included in the photometric extraction aperture, reducing the signal-to-noise ratio through an increase in read noise. In Figure 5, we present the difference in the effective resolution of a point source that occupies one pixel with and without moving target tracking. The WFI PSF is obviously larger than one pixel, but the results in Figure 5 can be applied to each pixel in the PSF, as well as each pixel in an extended object. Thus, this effect is even more significant for realistic point sources and extended objects. Moving target tracking is especially important for IFC observations of extended objects, such as the large satellites of Jupiter and Saturn (§4.2.1.1, §4.2.1.2, and §4.2.1.3), where spectral information for small regions of surface is desired; blurring of these extended sources would significantly reduce the spectral resolution of the data, and possibly render the observations useless for achieving the science goals. Other affected observations include spectral studies of giant planet atmospheres (§4.1.1 and §4.1.2) and comets (§4.3.7).



**Table 5. Impact assessment matrix**

	Giant planet atmospheres	Io volcanoes	Europa plumes	Titan clouds	Smaller giant planet satellites	Irregular satellites	Binary asteroids w/ CGI	Asteroid families	Active asteroids	Trojan asteroids	Centaur & KBOs	Comets	Inner Oort Cloud objects	Occultations
<b>No moving target tracking</b>	Red	Red	Red	Red	Red	Yellow	Red	Red	Yellow	Red	Yellow	Red	Green	Green
<b>No IFC</b>	Yellow	Red	Red	Red	Red	Green	Green	Red	Yellow	Green	Yellow	Red	Green	Green
<b>Both</b>	Red	Red	Red	Red	Red	Yellow	Red	Red	Yellow	Red	Yellow	Red	Green	Green

**Legend.** Red, yellow, and green boxes correspond to the three different levels of impact for the two potential cases of no moving target tracking and removal of the IFC. Red means that the entire science investigation, as outlined in §4, would no longer be feasible, yellow means that a large fraction of the science investigation would be significantly impacted, and green means that there would be no impact.



**Figure 5:** Effective resolution (a quantitative measure of the blurring of an object on the detector), measured in pixels, of a one-pixel point source with (red) and without (blue) moving target tracking. Objects moving up to 30 mas/s can be tracked exactly, resulting in no blurring; objects moving faster than 30 mas/s, including near-Earth asteroids (NEAs) and long-period comets would experience significantly less blurring by making use of the maximum track rate. Observations of all objects, even those moving at the slowest rates, would be affected if moving target tracking is not supported for WFIRST.

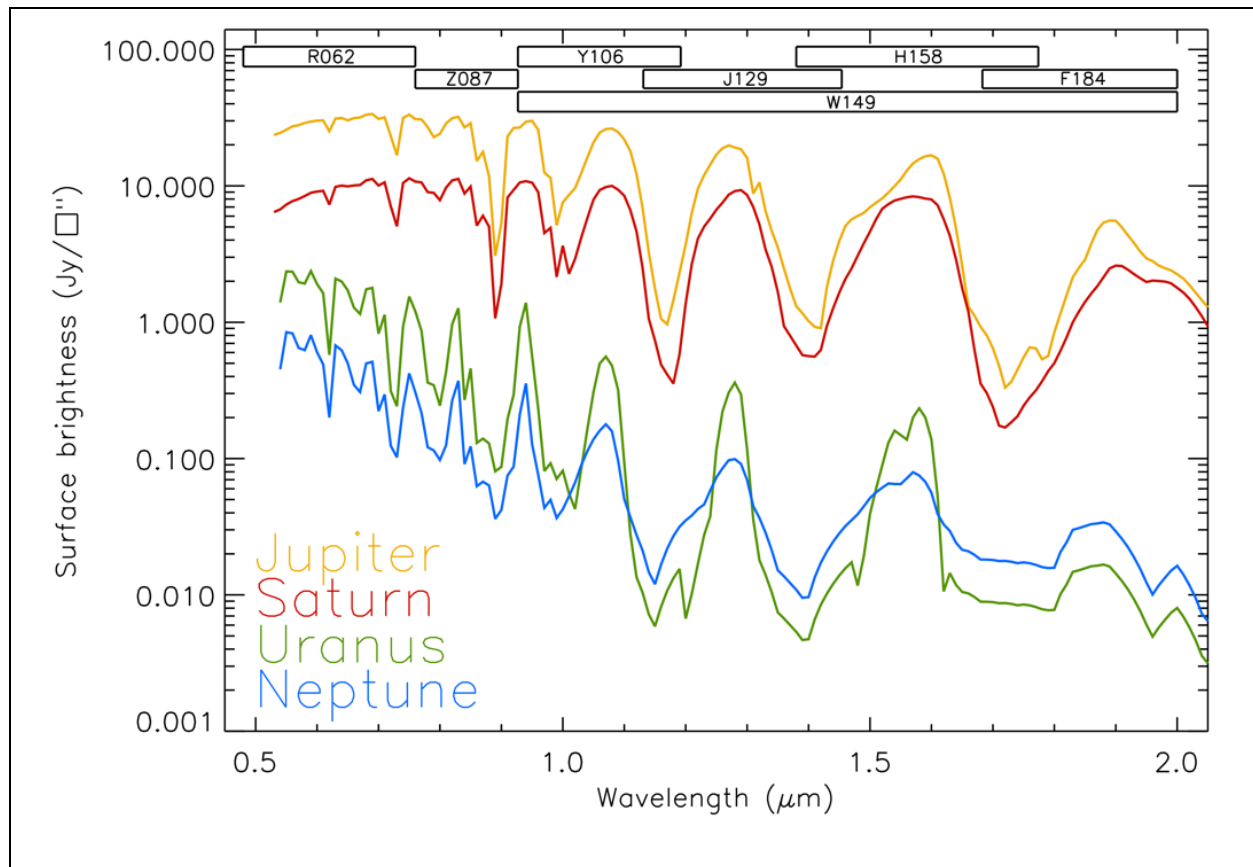
## 4. Solar system science: Guest Observer (GO) program

### 4.1. Giant planet atmospheres

The atmospheres of Jupiter, Saturn, Uranus, and Neptune are incredibly dynamic and still poorly understood. A better understanding of the chemical and meteorological processes in the atmospheres of the giant planets in our own solar system is also crucial for providing context for the larger population of exoplanets. WFIRST will contribute to the study of these atmospheres primarily through time-domain observations.

The full range of observations needed to study these dynamic atmospheres requires full rotational coverage, high-cadence observations, and long time-baselines. WFIRST is well-suited to carry out these observations and will provide continuity with existing Hubble imaging in the visible and near-infrared (e.g., Simon et al., 2015). Additionally, WFIRST will carry on the work of the Cassini spacecraft and prepare for a flagship mission to Uranus or Neptune in the 2030s and a potential future Saturn mission.

Imaging with the WFI and the various filters will reveal the morphology and vertical structure of clouds in the atmospheres of the giant planets. These filters sample a range of methane opacity, which in turn samples different altitudes on these planets. The Y106 filter, for example, sounds deep in the troposphere, while the F184 filter probes higher in the atmosphere due to methane absorption. Spatially-resolved spectroscopy with the IFC will yield the latitudinal profile of methane on each planet, which is required to infer cloud altitudes. Near-infrared spectra of the giant planets are presented in Fig. 6.



**Figure 6:** Surface brightness of the giant planets from 0.5 to 2.0  $\mu\text{m}$ . WFI filter bandwidths are presented as boxes across the top of the plot, with the filter name labeled within each box (see Table 1 for filter bandpasses). The smaller bandwidth filters will provide information on the vertical structure of giant planet atmospheres. Spectra calculated from Clark and McCord (1979), Karkoschka (1994), and Fink and Larson (1979).

#### 4.1.1. *Jupiter and Saturn*

The clouds and storms in Jupiter’s atmosphere are highly time-variable. Complete rotational coverage over one Jupiter day ( $\sim 10$  hours) is necessary to track the short-term evolution of some features; such observations can be difficult from the ground due to the night-length and changing atmospheric conditions. The Great Red Spot is an interesting feature to track over one rotation and study through multiple filters and spectroscopy. In the past 20 years, additional large storms have formed and changed color to a reddish hue, one by the merger of 3 smaller storms (Sanchez-Lavega et al., 2001). Two 60-year old storms merged 2 years prior, then merged with another 60-year old storm to form the new storm. This process, once started, took only 3 weeks. This illustrates the range of timescales over which observations must be made in order to fully understand this process from start to finish.

Every 20-30 years, a phenomenon referred to as the “Great White Spot” is observed in the atmosphere of Saturn (e.g., Sánchez-Lavega et al., 1991, 2012). These storms have a higher albedo than the surrounding atmosphere and alternate between the northern mid-latitudes and the equator. Interestingly, these storms have not been identified in the southern hemisphere. The Great White Spot was observed in 1990 and 2010, with the possibility that the next occurrence will be in 2030. Near-infrared observations of Saturn’s atmosphere during the lifetime of the WFIRST mission would provide valuable compositional information for testing current origin theories for these storms (Li and Ingersoll, 2015).

#### 4.1.2. *Uranus and Neptune*

Clouds were previously observed in the atmosphere of Uranus by Voyager 2 (Smith et al., 1986) and Hubble (e.g., Hammel et al., 2001; Sromovsky et al., 2009, 2015), allowing for a determination of wind velocities. Northern hemisphere winter will begin in 2028, during the WFIRST nominal mission; due to Uranus’ extreme axial tilt ( $\sim 98^\circ$ ), this means that the southern hemisphere is in complete darkness and the northern hemisphere is experiencing constant illumination. WFIRST could therefore enable the calculation of wind velocities surrounding Uranus’ North pole and provide further constraints for investigating seasonal variations on Uranus. These data would provide a useful comparison to the results reported from re-analyzed Voyager 2 images of Uranus’ South polar region (Karkoschka, 2015).

Clouds in Neptune’s southern hemisphere increased in size and albedo in the years leading up to the solstice in 2005 (northern winter/southern summer) (Sromovsky et al., 2003). Each season on Neptune spans  $\sim 40$  years, so seasonal changes are relatively slow, with the current increase in cloud activity thought to be observable until the early 2020s. WFIRST will be well-placed to observe this expected transition, as the midway point (cross-quarter) between the 2005 solstice and 2046 equinox occurs between 2025 and 2026.

Spectral imaging of Uranus and Neptune with the IFC will reveal  $\text{CH}_4$  profiles in these planets’ atmospheres as a function of latitude and altitude. The angular diameters of Uranus ( $\sim 3.7''$ ) and Neptune ( $\sim 2.4''$ ) will result in approximately 74 and 48 pixels across their disks, respectively, using the  $0.05''/\text{pixel}$  plate scale. The entire disk of Neptune will fit in the IFC FOV ( $3.0'' \times 3.15''$ )

and Uranus would require a  $2 \times 2$  mosaic to cover its entire disk. Time-domain studies over the life of the WFIRST mission would add the time dimension to these maps and provide a useful baseline for future space- and ground-based observing programs that aim to study the dynamics of the ice giant atmospheres.

## **4.2. Giant planet satellites**

Following the end of the Cassini mission in September 2017, there are no other missions planned to study the giant planet satellites that will definitely arrive at their destination prior to the launch of WFIRST: ESA's JUICE and NASA's Europa Clipper missions are currently slated to arrive in Jupiter orbit between 2025 and 2030, no Saturn missions are planned, and a Uranus or Neptune mission is in the early planning stages. WFIRST is therefore well-placed to provide preparatory observations of these satellite systems prior to any future missions and to help define their science objectives.

### *4.2.1. Spectra of giant planet satellites*

The WFIRST IFC will enable evaluation of temporal changes and surface compositions of the giant planet satellites (Fig. 7). The extreme volcanic activity of Io, ongoing evolution of Europa's surface, and the dynamic atmosphere of Titan present opportunities to observe short-scale temporal changes with time domain programs. The smaller satellites, on the other hand, record billions of years of solar system history in their radiation-processed surfaces. The study of both groups will further enhance our understanding of how and where the satellites of the giant planets formed and what physical and chemical processes are currently at work in their interiors, on their surfaces, and in their atmospheres.

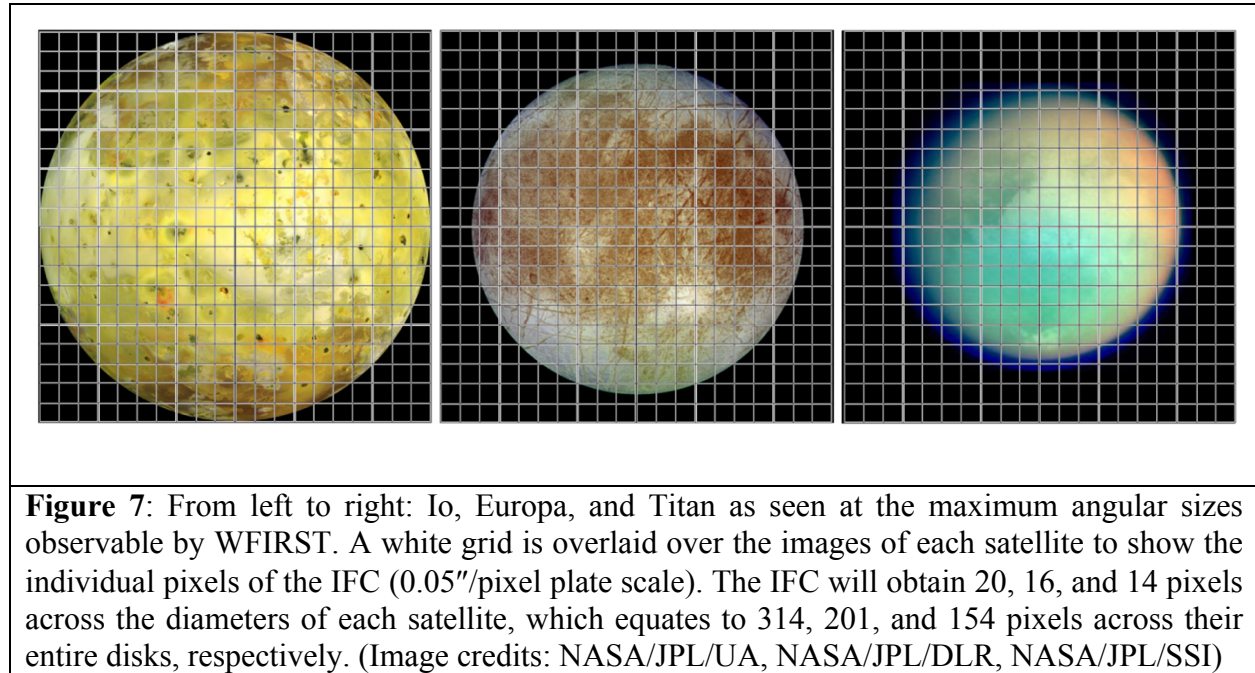
In particular, WFIRST will provide new insights into various aspects of the giant planet satellites by tracking surface features on Io, observing indirect evidence for ongoing plumes on Europa, tracking methane clouds on Titan, obtaining novel or improved surface spectra of other large and intermediate-sized satellites, and measuring the near-infrared spectral slopes of smaller satellites. Imaging spectroscopy in the near-infrared will enable identification and tracking of regions with potential volcanic activity on Io. Salts appear to weaken the water ice absorption bands on Europa's surface and may indicate areas of recent activity, inclusive of plume activity. Large-scale methane clouds on Titan provide clues to the interaction between Titan's surface and atmosphere on seasonal time scales. Calculation of near-infrared spectral slopes for a majority of satellites will enable comparison of surface properties between satellites and comparison to minor body populations for clues to the origins of the irregular satellites. Additionally, many intermediate-sized satellites in the outer solar system are irregular, a more in-depth look at their surface compositions will provide useful clues to their origins.

#### *4.2.1.1. Tracking volcanoes on Io*

Identification of ongoing volcanic activity on Io is best done between 3 and 5  $\mu\text{m}$ , a spectral regime outside of WFIRST's range (e.g., de Kleer and de Pater, 2016). Near-infrared observations between 0.6 and 2.0  $\mu\text{m}$  do not provide a definitive identification due to the contamination from reflected sunlight: bright regions may be regions of volcanic activity or high-albedo areas. However, such observations would provide useful information if they were made while Io is in Jupiter's shadow. This removes the flux due to reflected sunlight and any bright regions are therefore the result of thermal emission and possible volcanic activity. For 2 hours every  $\sim 42$  hours (Io's orbital period) Io is Jupiter's shadow, allowing many opportunities for these observations.



The spatial resolution of the IFC ( $\sim 20$  pixels across the disk) is sufficient for identifying large, hot regions (Fig. 7).



#### 4.2.1.2. Spectral evidence for plume activity on Europa

Salts and hydrated minerals, possibly brought to Europa's surface by plume activity, are easily detectable through identification of weakened water ice absorption features at the low spectral resolution ( $R \sim 100$ ) of the IFC (McCord et al., 1999). The composition of different areas of Europa's surface can be compared at the spatial resolution of the IFC ( $\sim 16$  pixels across the disk; Fig. 7).

#### 4.2.1.3. Tracking of clouds and surface features on Titan

Tracking of the seasonal methane clouds on Titan is possible at the spatial resolution provided by the IFC ( $\sim 14$  pixels across the disk; Fig. 7). A key focus area with WFIRST will be on methane windows at 0.85, 0.93, 1.08, 1.27, and 1.59  $\mu\text{m}$  for detection of clouds (Griffith et al., 2009) in the lower atmosphere. Surface water ice is indicated by low values of spectral ratios at 1.59/1.08  $\mu\text{m}$  and 1.59/1.27  $\mu\text{m}$  relative to the 1.27/1.08  $\mu\text{m}$  ratio (Rodriguez et al., 2006). Other spectral regions are indicative of different atmospheric gases, and organic haze composition (Bellucci et al., 2009; Clark et al., 2010).

#### 4.2.1.4. Spectral characterization of smaller satellites

The IFC can obtain spectra with an SNR of  $\sim 10$  in a 1000-second exposure for targets with V magnitudes of  $\sim 24.9$  (Spergel et al., 2015). This would result in new or improved spectra of most intermediate-sized giant planet satellites (e.g., Brown, 2000; Romon et al., 2001). It is likely that, due to the low signal-to-noise expected for the smaller, fainter satellites, only spectral photometry will be feasible and the spectra will need to be binned to a lower resolution.

#### 4.2.2. Irregular satellites

Further discovery and study of the orbits and physical characteristics of the irregular satellites of the giant planets will contribute to theories of the formation and evolution of the solar system. These satellites are in orbits that sometimes take years to complete and are likely minor bodies from other populations captured early in solar system history. WFIRST will help improve orbit characterization, gather color information, and increase the number of known irregular satellites, leading to clues about their origins and the dynamical evolution of the solar system.

In particular, WFIRST will enhance our understanding of the origins of the irregular satellites by increasing the sample size, improving upon previous orbital and color measurements, and obtaining new orbital and color measurements. Sub-groupings within each giant planet's irregular satellite population, such as the Himalia, Carme, and Ananke groups of Jupiter and the Gallic group of Saturn, share orbital and color characteristics, implying a common origin (Grav et al., 2003; Sheppard et al., 2003; Grav and Holman, 2004; Nesvorný et al., 2004). Comparison of these sub-groups to current minor body populations, such as main belt asteroids, comets, Centaurs, Trojans, and Kuiper Belt Objects, will shed light not only on the origin of the irregular satellites, but also the origin and evolution of these larger populations during the era of solar system formation (Nicholson et al., 2008).

Increasing the number of known irregular satellites requires deep imaging in a wide-band filter, a capability provided by the WFI and the W149 filter (0.927-2.000  $\mu\text{m}$ ). In a 1000s exposure, the WFI can image point sources down to  $V \sim 27.7$  in the H158 filter. This translates to the detection of irregular satellites down to approximately 0.3, 1.0, 4.5, and 11.4 km in diameter around Jupiter, Saturn, Uranus, and Neptune, respectively. For reference, the smallest currently known irregular satellites for each giant planet are 1, 0.3, 18, and 20 km in diameter, respectively. (The low value for Saturn is due to discoveries made with the *in-situ* Cassini spacecraft; WFIRST cannot reach this limit in a 1000 s exposure, but will have the benefit of a larger field of view compared to Cassini.) The search regions of interest around the giant planets (i.e., the solid angle of the Hill spheres as seen from Earth at opposition) are 4.7, 3.0, 1.5, and 1.5  $\text{deg}^2$ , respectively (Sheppard, 2006). With WFIRST's 0.28  $\text{deg}^2$  field of view, around 6-17 separate pointings, with two dithered images made at each pointing to cover chip gaps, are required to cover the search area surrounding each planet. Observations over multiple epochs will highlight the motion of new irregular satellites. Approximate J-H colors of a majority of known irregular satellites can be measured using the WFI and the J129 and H158 filters.

### 4.3. Minor bodies

#### 4.3.1. Binary asteroids with the CGI

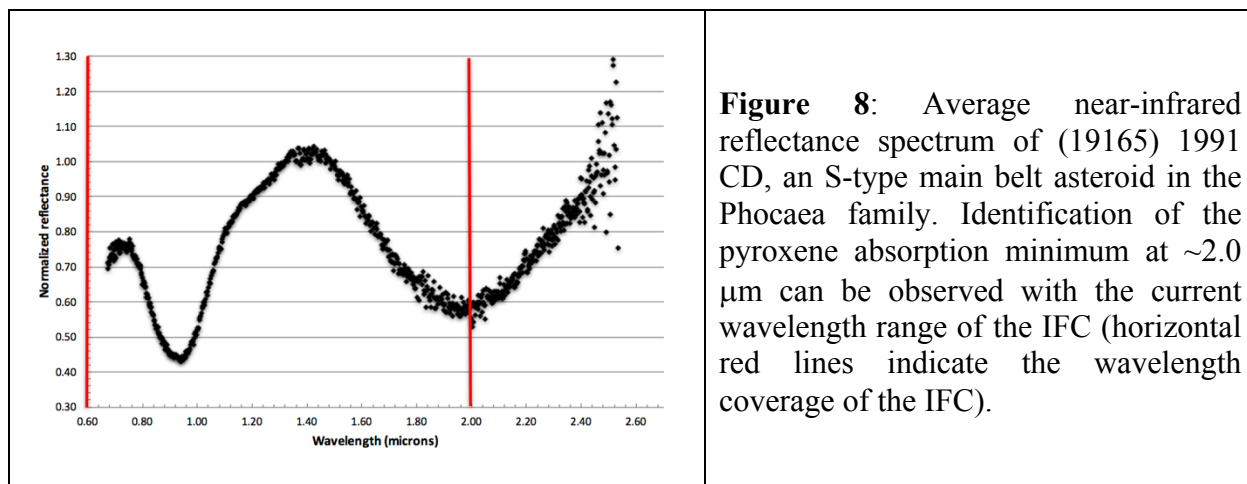
The CGI can be effectively used for observations of solar system objects, particularly for observations of binary asteroids and the detection of activity around active asteroids and Centaurs (see §4.3.3 and §4.3.5, respectively). In this section we focus on CGI observations of main belt asteroids in order to identify or confirm the presence of satellites. The study of binary asteroids is important for understanding the formation and physical processes that operated, or continue to operate, on these inner solar system minor bodies. Characterization of the satellite's orbit can provide mass and density estimates for the primary; the primary's porosity can also be constrained when taking into account information from rotation light curves. The CGI has an upper limit on the magnitude of  $V=14$ , rendering similar CGI observations of many Jupiter Trojans, Centaurs, and KBOs impossible.

The wavelength range of the CGI is 0.43-0.98  $\mu\text{m}$ , the inner working angle (IWA) is 0.15", and the magnitude difference ( $\Delta m$ ) between the primary and the secondary can be up to 9. Thus, the faintest detectable satellite is  $V=23$  (5- $\sigma$  detection), and the IWA corresponds to 220, 325, 430, and 540 km at 2, 3, 4, and 5 AU, respectively. Observations of faint satellites with short orbital periods are therefore possible with the CGI. However, it is recommended that only known binary systems and asteroids with suggestive rotation light curves be targeted for these observations; blanket observations of a large number of asteroids are unlikely to yield useful results and would not be an efficient use of time. As an example, the Ida/Dactyl system, with Ida at  $V=13.6$  and  $\Delta m=6.7$ , is composed of a primary and a satellite with mean diameters of 31.4 and 1.4 km, respectively (Belton et al., 1996a; Veverka et al., 1996). The semi-major axis of Dactyl is not well-constrained (between 85 and 355 km), but additional constraints could be placed on its orbit with WFIRST imaging observations (Belton et al., 1996b). At  $\sim 2.8$  AU from the Sun, Dactyl could be observed with the CGI if its semi-major axis is on the larger end of the range. Discovery of similar asteroid binaries is presently only possible with spacecraft flybys, but an increase in the number of known systems is possible with WFIRST and the CGI.

#### 4.3.2. Asteroid families

The study of asteroid families within the main asteroid belt, which represent disrupted parent bodies or swarms of fragments ejected from a parent asteroid's surface, informs compositional, taxonomic, and dynamical questions concerning asteroid family origin and evolution (e.g., Milani et al., 2014; Nesvorný et al., 2015; Spoto et al., 2015). In particular, questions concerning actually genetic family membership, the presence of interlopers (i.e., non-genetic family members) among a family population, family space weathering trends, and the ability of asteroid taxonomies to correctly identify family members are issues that must be addressed to accurately determine the distribution and abundance of genetic asteroid family members (e.g., Fieber-Beyer et al., 2011; Thomas et al., 2011; Hardersen et al., 2014; Reddy et al., 2014; Ali-Lagoa et al., 2016; Paolicchi and Knežević, 2016; Migliorini et al., 2017). Only through accurate identification of family members that originated from their respective parent asteroids can rigorous compositional and dynamical studies of individual families be conducted.

Observations utilizing the WFIRST IFC to conduct low-resolution ( $R \sim 100$ ) visible- and near-infrared reflectance spectroscopy has the potential to more strongly constrain the genetic asteroid family membership for many asteroid families as well as test asteroid family taxonomic classifications. Acquisition of spectra from 0.6 to 2.0  $\mu\text{m}$  outside of the obscuring telluric features of Earth's atmosphere and using the full WFIRST 2.4-meter telescope aperture will allow the detection of mineral absorption features that include olivine ( $\sim 1.0 \mu\text{m}$ ), pyroxene ( $\sim 0.9$  and  $\sim 1.9 \mu\text{m}$ ; Fig. 8), spinel ( $\sim 1.4 \mu\text{m}$ ), and possibly phyllosilicates ( $0.7 \mu\text{m}$ ). Detection of these mineral absorption features will allow direct spectral and mineralogical comparisons between potential family members and the parent body, to discover non-family interlopers or diversity among a family via detections of different mineral(s), and to verify or reject a presumed mineralogy/composition based solely on a taxonomic classification.

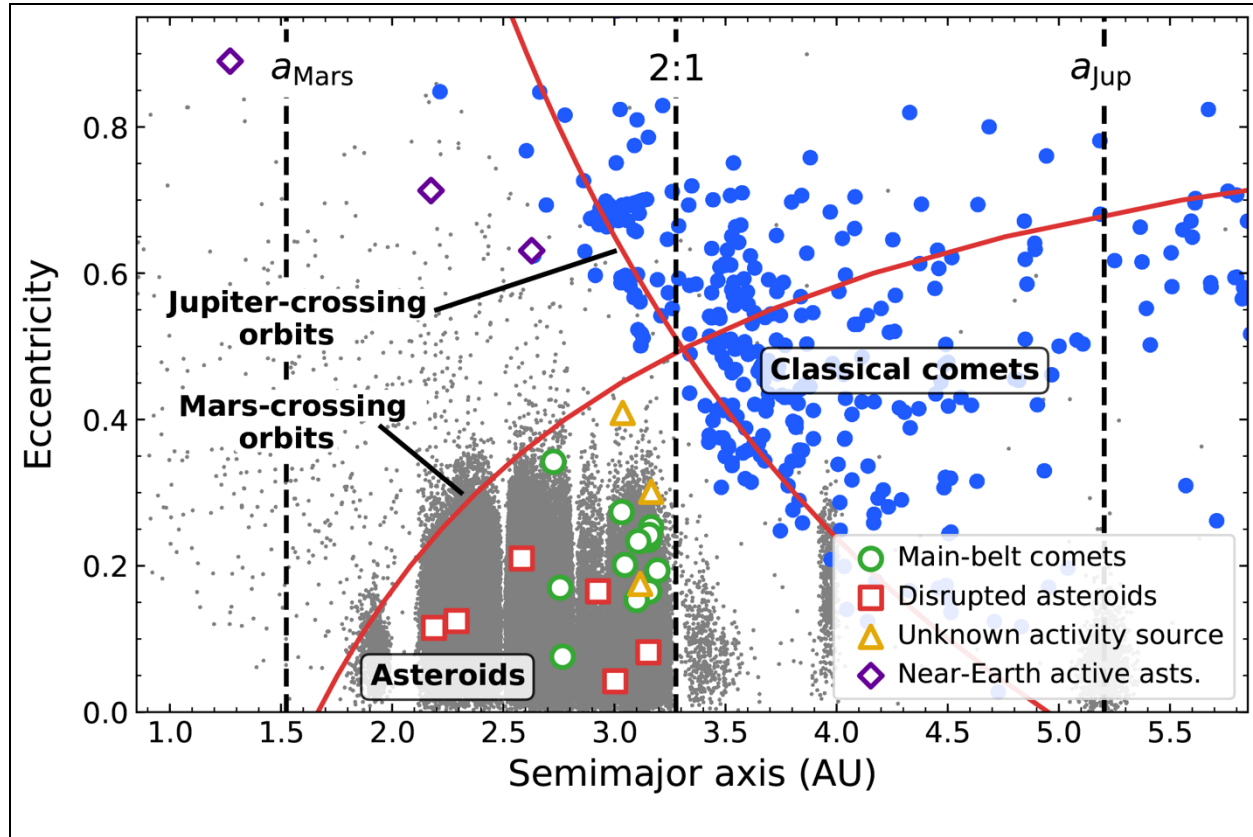


#### 4.3.3. Active asteroids

Active asteroids (Jewitt et al., 2015) are a newly recognized classification of solar system minor bodies that possess asteroid-like dynamical properties (typically defined as having a Tisserand parameter with respect to Jupiter of  $T_J > 3$ ; Fig. 9) but exhibit mass loss similar to comets. They include main-belt comets (MBCs; e.g., Hsieh and Jewitt, 2006), which orbit in the main asteroid belt and whose dust emission is due to the sublimation of volatile ice, and disrupted asteroids, whose dust emission is due to physically disruptive processes such as impacts or rotational destabilization rather than sublimation (e.g., Hsieh et al., 2012). Main-belt comets present an opportunity to study the nature, extent, and abundance of ice in inner solar system bodies and have implications for understanding the formation of our solar system and delivery of water to the early Earth. Disrupted asteroids present opportunities to study disruptive processes on small bodies in real time for comparison to theoretical models of those processes and also for inferring properties of their interiors. Discovery of more such objects (e.g., Hsieh et al., 2015) is crucial for advancing our understanding of their abundance and distribution in the inner solar system and the ranges of various physical properties associated with these objects (e.g., sizes, activity levels, active lifetimes, rotation periods, colors, etc.). Observations with the CGI can be used to detect or confirm activity around active asteroids. Discovery of additional active asteroids by WFIRST will increase the known population of these objects and enable follow-up by other ground- and space-based telescope facilities.

Serendipitous detection of MBCs and other active asteroids will be conducted using data obtained as part of the already planned WFIRST high-latitude (§5.1) and microlensing surveys (§5.2). The WFIRST wavelength range should make it more sensitive to large dust particles which should persist longer for active objects (provided that they can be ejected at speeds greater than the active object's escape velocity), widening the observability window for detection of active events. Given the field positions of these surveys (mostly far from the ecliptic), we do not expect a large number of MBCs to be discovered. There may, however, be the opportunity for discovery of non-main-belt active asteroids or other low-activity cometary bodies among the near-Earth object population which has a substantially broader inclination distribution (and therefore a broader ecliptic latitude distribution) than the main-belt asteroid population. A Guest Observer (GO) survey program to identify new active asteroids may be more successful, though more limited in observing time. Additionally, targeted observations of currently known active asteroids

by WFIRST would extend the time-baseline of observations for the purpose of measuring potential changes in activity.



**Figure 9:** Semi-major axis vs. eccentricity for asteroids (small gray dots), classical comets (blue circles), and various kinds of active asteroids (open colored symbols). Likely main-belt comets are marked with open green circles, likely disrupted asteroids are marked with open red squares, active asteroids whose activity sources are currently unknown are marked with open orange triangles, and near-Earth active asteroids (i.e., those not found in the main asteroid belt but which have asteroid-like Tisserand’s parameters with respect to Jupiter,  $T_J$ ) are marked with open purple diamonds. Red curves represent Mars- and Jupiter-crossing orbits, while vertical dashed lines mark, from left to right, the semi-major axis of Mars, the 2:1 mean-motion resonance with Jupiter, and the semi-major axis of Jupiter. Active asteroids are clearly dynamically distinct from other comets, and most are dynamically indistinguishable from main-belt asteroids.

#### 4.3.4. Trojan asteroids

The origin of Jupiter’s Trojan asteroids is still up for debate, and with the discovery of two distinct compositional classes (e.g., Emery et al, 2011), there may not be just one answer. These two classes have different near-infrared colors (Emery et al., 2011) and spectral properties, suggesting two different origins; the L4 and L5 clouds are home to members of both compositional classes. WFIRST can provide near-infrared colors with the WFI and near-infrared spectra with the IFC of more Jupiter Trojans, enabling comparison to the irregular satellites and other minor body populations like main belt asteroids, Centaurs, and KBOs. The Jupiter Trojans either have two very distinct origins or have the same origin and are drawn from a population with a wide range of colors (Wong and Brown, 2016). Colorimetry of currently known Jupiter Trojans that lack near-

infrared colors would increase the sample size for determining whether or not transition objects exist and thus enable a more thorough assessment of the origins of the two distinct populations.

In the past two decades, two different theories have been proposed for the origin of the Jupiter Trojans: in-situ formation and capture. The idea of in-situ formation is based on the assumption that the Trojan asteroids are remnants of the formation of the giant planet satellites that formed in a circumplanetary disk of “satellitesimals.” During the formation of the satellites, some of these small bodies were captured into Trojan orbits. The capture idea is based on the assumption that after the formation of the giant planets, their induced migration due to interaction with the leftover planetesimals might have resulted in the scattering of some of these objects and their subsequent capture at giant planets’ Lagrange points. Current observational evidence indicates that the color distribution of the Trojans is nearly identical to that of Kuiper Belt Objects (Wong and Brown, 2017). This favors the idea of the Jupiter Trojans having been captured from leftover planetesimals.

WFIRST is also well-placed to provide supporting observations of the Jupiter Trojans for the JAXA Solar Power Sail and NASA’s Lucy Discovery-class mission (§2.4), both of which are set to launch in the early 2020s and make close flybys of Trojan asteroids later that decade. Characterization of the flyby targets by WFIRST will enhance the scientific gains from these missions by tying high-resolution imaging and spectroscopy together with population-wide trends for a more comprehensive evaluation of Trojan origins.

Earth, Mars, Uranus, and Neptune are also known to have Trojan populations. One Earth Trojan was recently identified (Connors et al., 2011) and WFIRST could identify additional members: Assuming WFIRST is positioned at the Earth-Sun L2 point, the solar elongation angle of the L4 and L5 points is  $\sim 59^\circ$ , within the field of regard (Fig. 3). (WFIRST will actually execute a small orbit about the L2 point, but the geometry remains roughly the same along the orbit.) The Mars Trojans are thought to be related to main belt asteroids (Rivkin et al., 2007), the Uranus Trojans have short lifetimes and may be captured Centaurs (Alexandersen et al., 2013), and the Neptune Trojans likely migrated outwards with Neptune early in solar system history and are similar to KBOs (Sheppard and Trujillo, 2006). For further information on potential WFIRST observations of these Trojan populations, see §4.3.2, §4.3.5, and §4.3.6, respectively.

#### *4.3.5. Centaurs*

Centaurs are thought to be a transition population between Kuiper Belt Objects (KBOs) and the Jupiter Family Comets (JFCs), but their origin and evolution remain poorly understood. Two aspects of Centaurs could provide the observational evidence needed for a better understanding of this population: cometary activity and the red/gray dichotomy in the color distribution of Centaurs.

Some Centaurs have been found to be active (e.g., Chiron, LONEOS, Gibbs, 166P, Echeclus, 29P), but cometary activity is very weak for most ( $<30$  kg/s) or entirely absent (e.g., Jewitt, 2009). A survey of cometary activity among Centaurs is fundamental to understand if they have a common origin or if there is a difference in origin and evolution between active and non-active Centaurs. Moreover, to relate mass loss rate due to cometary activity to other parameters, both orbital (e.g., inclination and heliocentric distance) and optical (e.g., albedo and color), it is important to reconstruct the dynamical history of these objects. The detection of gas commonly related to cometary activity has been successful on a few Centaurs, but for many of them only an upper limit of their abundance has been given (e.g., Rauer et al., 1997, Paganini et al., 2013). Observations with the CGI can be used to detect activity around Centaurs. Detection and abundance of these gases or volatile ices, such as ammonia ( $\text{NH}_3$ ), methane ( $\text{CH}_4$ ), CO,  $\text{CO}_2$ ,

methanol ( $\text{CH}_3\text{OH}$ ), ethane ( $\text{C}_2\text{H}_6$ ), acetylene ( $\text{C}_2\text{H}_2$ ), hydrogen cyanide ( $\text{HCN}$ ), as well as amorphous and crystalline water ice, is fundamental to answer this question.

Centaurs are grouped in two main families based on visible color (e.g., V-R, B-R). “Red” and “gray” Centaurs are two distinct families, and no transition objects between the two families have been observed (e.g., Tegler et al., 2016). This suggests differences in origin and/or dynamical evolution. In the first scenario, red and gray Centaurs formed at different heliocentric distances in the solar nebula, with the red Centaurs retaining materials thought to result in more pronounced surface reddening (e.g.,  $\text{CH}_4$  and  $\text{CH}_3\text{OH}$ ; Brown et al., 2011). In the second scenario, the red Centaurs are more primitive and went through fewer periods of cometary activity than the gray Centaurs, implying that the gray Centaurs underwent significantly more dynamical evolution. Previous work aimed at testing these scenarios by investigating correlations between color, albedo, and orbital parameters (e.g., semi-major axis, inclination, eccentricity, perihelion distance). It was found that gray Centaurs have higher inclination angles and lower albedos than the red Centaurs; no correlations were identified between color and the other orbital parameters (Bauer et al., 2013; Tegler et al., 2016). The lack of correlation between color and a majority of the orbital parameters suggests the former scenario (differences in origin) may be the most accurate explanation, but a larger sample of near-infrared colors and spectra is needed to confirm this result.

Spectroscopy with the IFC will allow detection of most of the volatile elements that may exist on the surfaces of Centaurs. The IFC is sensitive at wavelengths where absorption features and overtones of amorphous water ice ( $1.65\text{ }\mu\text{m}$ ), crystalline water ice ( $1.5\text{ }\mu\text{m}$ ),  $\text{CO}$  ( $1.6\text{ }\mu\text{m}$ ),  $\text{NH}_3$  ( $1.52\text{ }\mu\text{m}$ ),  $\text{CH}_4$  ( $1.65\text{ }\mu\text{m}$ ),  $\text{CO}_2$  ( $1.6\text{ }\mu\text{m}$ ),  $\text{CH}_3\text{OH}$  ( $1.2$ ,  $1.56$ , and  $1.72\text{ }\mu\text{m}$ ),  $\text{C}_2\text{H}_6$  ( $1.54\text{ }\mu\text{m}$ ),  $\text{C}_2\text{H}_2$  ( $1.53\text{ }\mu\text{m}$ ), and  $\text{HCN}$  ( $1.5\text{ }\mu\text{m}$ ) are present. The IFC data will also allow for measurements of the infrared spectral slope and to relate it to band depths of volatiles. Other important measurements, particularly those of fainter Centaurs, will be possible by the imager, which covers the  $0.6$ - $2.0\text{ }\mu\text{m}$  wavelength range. In particular, calculation of near-infrared albedos and color indices will allow for discrimination between a larger number of red and gray Centaurs, as well as a comparison to the distributions of visible albedo and color indices. Additionally, WFIRST’s field of regard covers all declinations between the North and South ecliptic poles (with observable right ascensions dependent on the time of year), enabling observations of recently discovered high-inclination Centaurs (Brasser et al., 2012; de la Fuente Marcos and de la Fuente Marcos, 2014; Chen et al., 2016). These Centaurs, while only a small sub-set of the entire population, may be related to comets from the Oort Cloud and determination of their colors and surface compositions should provide further information for evaluating current theories of Centaur origins and evolution.

#### 4.3.6. Kuiper Belt Objects

Based on dynamical considerations, the population of Kuiper Belt Objects (KBOs) is the likely reservoir of the Centaurs and Jupiter Family Comets (JFCs), both of which are relatively short-lived relative to the 4.5 Gyr history of the solar system. KBOs, including the dynamically-excited KBOs, likely formed in the outer solar system and were swept out to their present location and emplaced via resonances with Neptune (e.g., Dones et al., 2015). There they have resided for most of the age of the solar system, and because they have not undergone a prolonged period of intense insolation, are primitive samples of the solar system’s primordial composition. Over time, these bodies may be perturbed into planet-crossing orbits and evolve first into Scattered Disk Objects (Gladman et al., 2002), and then Centaurs (e.g., Trujillo and Brown, 2002; Horner et al., 2004), which in turn may evolve into JFCs through continued interaction with Jupiter.



The compositional link is less clear, however, between KBOs and the Centaurs and JFCs. As mentioned in the previous section, Centaurs fall into two different color groups, with minimal correlation between color and dynamical properties. KBOs have red and gray sub-populations (e.g., Tegler et al., 2016) that are more clearly correlated with their dynamical properties (Trujillo and Brown, 2002), but the correlation between the KBO and Centaur color groups is not established, nor is the compositional source of these color differences, though different theories have been proposed (e.g., Brown et al., 2011). Further comparison of the color distributions of the Centaur and KBO populations, particularly the Scattered Disk Objects, is needed to assess potential links between the two populations.

Visible colors provide information on spectral slope whereas near-infrared colors provide information on surface composition due to the prevalence of ice absorption features. The WFIRST WFI and its suite of filters will allow for comparison of KBO and Centaur colors in a different wavelength regime. Similar distributions in near-infrared colors, as noticed for the visible colors (Pike et al., 2017), would suggest similar surface compositions and provide a stronger link between the two populations. In a 1000s exposure, WFIRST can observe objects at the 5- $\sigma$  level with a V magnitude of 27.6, 27.7, and 27.8 in the Z087, J129, and H158 filters, respectively. This corresponds to a 5- $\sigma$  detection of KBOs at 40 AU with diameters of  $\sim 10$  km in each filter. Significantly higher SNR can be achieved on brighter objects, a category that includes most, if not all, currently known KBOs and Centaurs.

Time-domain studies of larger objects on yearly timescales, such as Pluto and the captured KBO Triton (Agnor and Hamilton, 2006), inform the ongoing physical and chemical processes on these objects. Changes in surface composition have been identified on both Pluto (Grundy et al., 2014) and Triton (Holler et al., 2016) on the timescale of a decade. Continued near-infrared spectral observations of these objects will be important in the latter half of the 2020s as Pluto moves away from the Sun, potentially resulting in atmospheric changes, and as the sub-solar latitude on Triton moves further north, revealing regions previously in constant darkness for decades. WFIRST may be the only space-based facility capable of these observations during this time. In 1000 seconds, the IFC can obtain an SNR of 10 in each  $R \sim 100$  resolution element for a  $V \sim 24.9$  object. The IFC would therefore provide high-SNR near-infrared spectra of Pluto and Triton for time-domain studies.

Additionally, continued study of KBO binaries and multiple systems, of which over 80 are currently known, will be valuable in that they provide mass and density constraints on the system as a whole. However, it is not clear how these systems formed, whether through co-formation, collisions, or capture (e.g., Noll et al., 2008). By identifying and comparing colors and compositions, we can assess potential genetic links between members of particular systems. The angular resolution of the WFI is adequate for separating a handful of KBO binary systems, including Pluto/Charon, Eris/Dysnomia, Haumea/Namaka/Hi'iaka, Quaoar/Weywot, Teharonhiawako/Sawiskera, and Mors-Somnus, among others. See §5.2 for a more in-depth discussion of KBO satellite observations with WFIRST.

#### 4.3.7. *Comets*

Comets are remainders from the time of the formation of the giant planets and serve as a probe of primitive composition. Comets can be broadly grouped into two categories based on their orbital characteristics: Jupiter Family Comets (JFCs; short-period comets) and Oort Cloud comets (long-period comets). JFCs typically have orbital periods  $< 20$  years and low inclinations; their orbits have been shaped by gravitational interactions with Jupiter. The long-period comets have

more elliptical orbits, cover a large range of inclinations, and originate in the Oort Cloud, a spherical reservoir of minor bodies beyond the Kuiper Belt. While comets are most recognizable by their activity (the presence of a cloud of dust and gas and/or dust tails), other potentially active objects include active asteroids, main belt comets (§4.3.3), and Centaurs (§4.3.5). WFIRST will be able to observe comets beyond where water-sublimation is dominant over other species ( $< 2.5$  AU), and reveal the comet surfaces and activity onset and diminishment for species not previously characterized. Since dust characteristics are best studied at near-IR wavelengths (§4.3.7.2), WFIRST fills a critical niche in wavelength space. Here, we will demonstrate how WFIRST will complement JWST in wavelength, characterize surface absorption features of the nucleus in each high-SNR channel of the IFU, and utilize the statistical survey sampling afforded by the WFI. We define three science cases where WFIRST can play a key role:

- How many comets are in the Oort Cloud?
- What are the properties of cometary ice?
- What are the sizes and shapes of cometary nuclei?

Before we can address those questions, we will need to assess how many comets are observable by WFIRST. For this, we repeated the JWST non-sidereal rate study by Kelley et al. (2016) using WFIRST's solar elongation constraints (Fig. 10). In brief, they considered all known comets with perihelion dates between January 2010 and January 2015, independent of their discovery circumstances: 221 short-period and 172 long-period comets. We find that WFIRST can observe a greater fraction of comets than JWST due to the wider field of regard ( $54^\circ$ – $126^\circ$  versus  $85^\circ$ – $135^\circ$ ), despite the same rate limit of 30 mas/s. Moreover, long-period comets are much better observed within the inner solar system. However, this tracking limit still misses many observing opportunities: approximately 43% of the targets at  $r_h=1.5$  AU can be tracked, dropping to 20% at 1.2 AU. Ensuring a robust non-sidereal tracking limit is critical for obtaining observations of bright and active comets near the Sun and Earth. Doubling the non-sidereal tracking rate from 30 mas/s to 60 mas/s would significantly increase the number of comets observable by WFIRST, especially long-period comets, and enable more detailed spatial studies of the inner structure of comet comae.

Present estimates of cometary populations suggest considerable numbers of cometary bodies will be accessible to WFIRST observations. In order to establish lower bounds, we neglect activity and assume bare cometary nuclei albedos are  $\sim 5\%$ , similar to some other outer solar system populations (e.g., Grav et al., 2012). This means that WFIRST, with magnitude limits approaching  $V=26$  or more, will be capable of detecting objects down to sizes of  $\sim 1$  km beyond Jupiter's orbit. The total population of JFCs has been estimated to be  $\sim 2000$  (Bauer et al., 2017). For long-period comets within 8 AU, lower limits suggest  $\sim 1000$  comets per year will be observable by WFIRST, both in their quiescent and active phases. Not all will be observed, either in passive surveys or as targets, but even a small subset would yield significant statistical constraints.

#### *4.3.7.1. How many comets are in the Oort Cloud?*

The densities of the populations of the primordial comet reservoirs set primary constraints on the formation and evolution of the early solar system. Linked to these quantities is the determination of the amount and nature of material presently available within the Oort Cloud (Kaib and Quinn, 2009; Levison et al., 2010). The Oort cloud is the solar system's "deep freeze storage," where material is best preserved in its original form against the effects of insolation from the time

of its emplacement. It is also the direct source of long-period comets (Dones et al., 2015). However, the current estimates of the mass of the Oort cloud are based on comets that get relatively close to the Sun. These constraints, largely based on careful de-biasing of surveys, have set meaningful order-of-magnitude estimates (e.g., Oort, 1950; Francis, 2005; Bauer et al., 2017), yet have their limitations. Specifically, the effect of giant planet perturbations in curtailing the influx of cometary bodies from the outer solar system, as manifested in the so-call “Jupiter barrier” effect, cannot be directly assessed through surveys dominated by comets in near-Earth orbits, as assumptions rely on discovery of comets within heliocentric distances where water-sublimation dominates. WFIRST’s sensitivity can be used to identify and characterize activity in much more distant comets, and thereby to assess the number of active comets beyond Jupiter’s orbit, relative to the presently observed fluxes within. Recent infrared observations (Ootsubo et al., 2010; Reach et al., 2013; Bauer et al., 2015; Kelley et al., 2017) have shown volatile species, other than water, that are more active (Meech and Svoreň, 2004) at greater distances are ubiquitous. WFIRST can therefore place important constraints on solar system formation theories and comet evolution. Large space-based surveys, owing to their systematic sampling unencumbered by variable seeing and weather, would also be easier to de-bias (Bauer et al., 2017) than ground-based surveys of comparable and even lesser depth. Large area imaging surveys with the WFI will allow us to quantify how long activity persists and at the same time to make the deepest inventory of distant comets and their reservoirs yet.

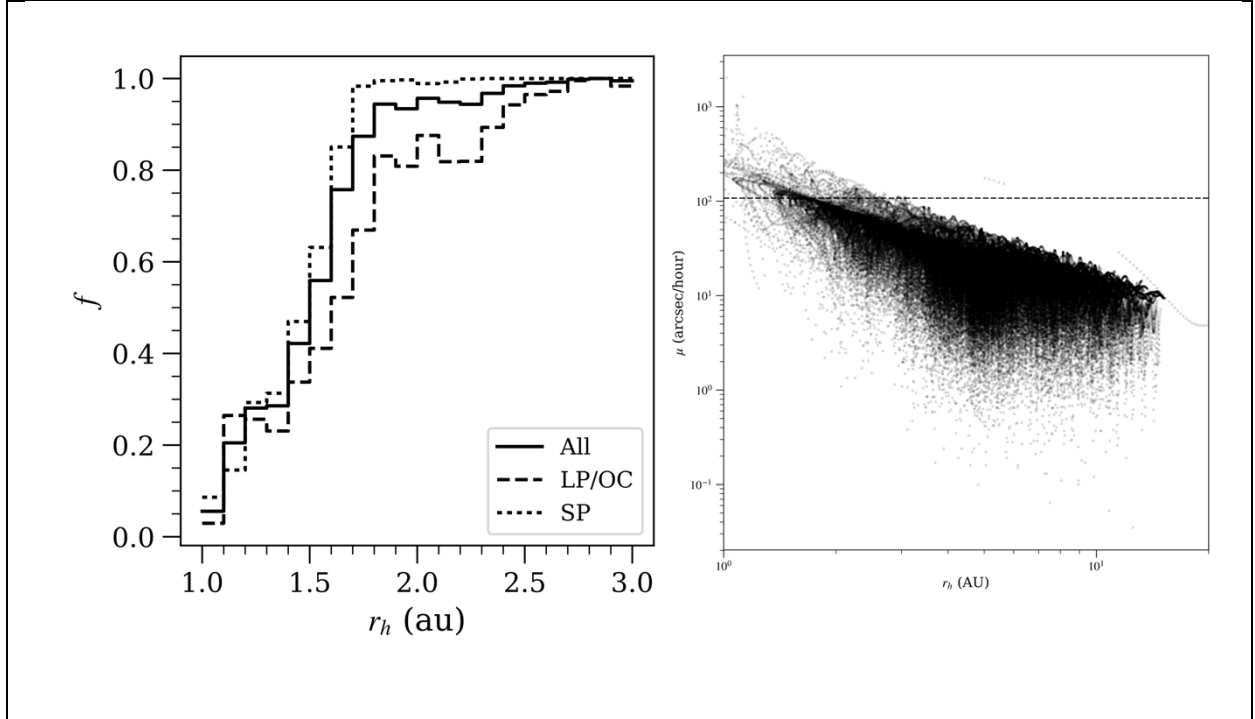
#### *4.3.7.2. What are the properties of cometary ice?*

Water ice is a key component of comets and was a significant planet-building material in the early solar system beyond the frost line. Therefore, assessing the physical properties of water ice in comets is essential to test comet nuclei formation scenarios. WFIRST’s filters are too broad to determine the presence or absence of water ice absorption bands; however, the IFU has sufficient spectral coverage and resolution to map the water-ice distribution on the surface and in the comae of comets through analysis of the amorphous 1.5  $\mu\text{m}$  and crystalline 1.65  $\mu\text{m}$  water ice absorption bands. A quantitative assessment of water ice grain sizes would only be possible by extending the long-wavelength limit of the IFC to  $>2.2 \mu\text{m}$  in order to disentangle the effects of grain size and abundance using the 1.5  $\mu\text{m}$  and strong 2.0  $\mu\text{m}$  water ice absorption features (Protopapa et al., 2014). Sub- $\mu\text{m}$  grains present a strong absorption feature at 2.0  $\mu\text{m}$ , but not at 1.5  $\mu\text{m}$  (Yang et al., 2014); the IFC wavelength range, as currently defined, does not provide full coverage of the broad 2.0  $\mu\text{m}$  absorption feature.

#### *4.3.7.3. What are the sizes and shapes of cometary nuclei?*

WFIRST will be able to constrain the sizes, shapes, and albedos of cometary nuclei by combining high angular resolution with the increased nucleus-coma brightness ratio provided by near-infrared IFC observations. Currently, a small sample of comet nuclei have been studied using coma extraction techniques (Lamy et al., 2004; Fernández et al., 2013; Bauer et al., 2015, Bauer et al., 2017). The removal of residual comae, possibly extant even at larger distances (e.g., Bauer et al. 2015) will be enabled by the high resolution and WFIRST’s stable and well-characterized PSF, as the coma extraction techniques fit the wings of the dust coma with a  $(1/r)^n$  profile and extrapolate to the nucleus PSF. WFIRST has an advantage over optical HST observations in that much of the near-infrared lacks any significant gas emission bands, effectively increasing the nucleus-coma brightness ratio, and facilitating the fidelity of the single-index profile model along limited azimuthal ranges to the actual coma signal. Second, the sensitivity of WFIRST allows for

observations at greater distances when the object is less active. Finally, the angular resolution of the WFI is slightly higher in the near-infrared than in the WFC3 infrared channel on HST (0.11 vs. 0.13 "/pixel). By noting surface constituents, through spectroscopic features of silicates, darkening agents like amorphous carbon, and ice species (§4.3.7.2), better estimates of surface albedos can be achieved.



**Figure 10:** Fraction of comets observable by WFIRST as a function of heliocentric distance (left panel). The dotted line represents short-period comets, the dashed line long-period comets, and the solid line all comets. Comets at smaller heliocentric distances will be moving at a faster non-sidereal rate than those farther away. Additionally, short-period comets are more likely to be observable due to their lower velocity compared to the long-period comets, which are on highly eccentric orbits. The nominal 30 mas/s tracking limit places a significant limit on observations of comets and their nuclei within 2.0 AU of the Sun. In the right panel, the apparent rate as a function of heliocentric distance for short- and long-period comets is presented; only times when the comets are within WFIRST's field of regard are considered. The dashed line marks the 30 mas/s nominal tracking limit for WFIRST.

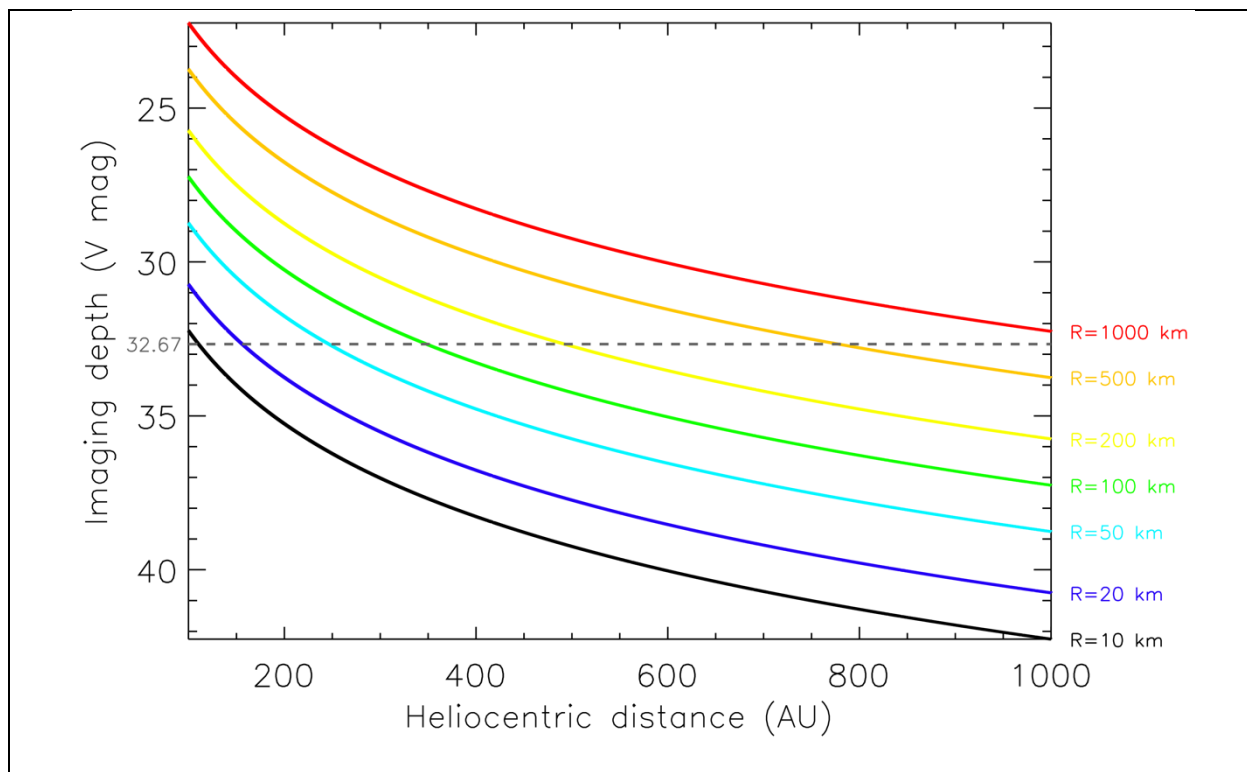
#### 4.3.8. Inner Oort Cloud objects

The most distant solar system minor bodies are time capsules that preserve information from the formation of the solar system. Long-period comets are members of this population and provide useful compositional information, but we must wait until they make the long journey to the inner solar system. It is also unknown just how many of these objects are present in the outer reaches of the solar system. Identification of objects orbiting at large heliocentric distances would be the next step in understanding the formation and evolution of the solar system, and would provide better context for the population of long-period comets and various KBO populations, including the scattered disk objects (SDOs) and detached (large-perihelia) objects.

At the present time, no objects have been detected orbiting the Sun at distances  $>100$  AU; the farthest known object at this time is the large KBO Eris, orbiting  $\sim 96$  AU from the Sun. The region beyond the Kuiper Belt, but interior to the Oort Cloud proper, is sometimes referred to as the “Inner Oort Cloud” or the “Hills Cloud” (Hills, 1981). Many objects have been identified with orbits that take them beyond 100 AU, but none have been detected while in this region, likely because of the extremely large orbital distances and physical characteristics of these bodies (small size, low albedo) that combine to produce very low reflected flux. High sensitivity and large amounts of observing time are required to make a detection of a small body beyond 100 AU.

The limiting  $V$  magnitude for detection in a 10,000-second exposure through the W149 filter, the WFI filter with the broadest available bandpass, is 32.67. Scaling fluxes from Charon, using the geometric albedo and radius from Stern et al. (2015) and the heliocentric distance, geocentric distance, and  $V$  magnitude on an arbitrary date from JPL Horizons, we calculated the  $V$  magnitude for Inner Oort Cloud objects of varying sizes and heliocentric distances (Fig. 11). We assumed a geometric albedo for these objects of 0.04, similar to long-period comets. Based on these results, a 1000-km object would be detectable at distances  $>1000$  AU, while a 10-km object could be detected at a distance of only 110 AU.

The Oort Cloud is theorized to be a spherical distribution of comets, meaning the distribution of objects across the sky is relatively uniform (Oort, 1950). However, the shape of the Inner Oort Cloud is possibly more disk-like, centered on the ecliptic, with a larger spread in ecliptic latitude with increasing heliocentric distance. This means a higher density of objects in a smaller area of sky, increasing the chances that any particular pointing could detect an Inner Oort Cloud object. A potential Inner Oort Cloud survey could be combined, as a GO program, with a deep imaging survey of faint astrophysical sources, such as high-redshift galaxies, that would not be detected as part of the currently planned surveys. The ideal survey region would be a few tens of degrees above or below the ecliptic plane to avoid the majority of minor bodies in the solar system, and outside of regions heavily populated with galaxies, to avoid source confusion. The general strategy would be to obtain a 10,000-second exposure of a particular area of sky, then come back at a later time (no later than 1 day) and obtain another 10,000-second exposure with the field offset in order to increase in the survey field while probing deeper than a single exposure could provide. The overlap of the two fields should be  $\sim 25\%$  for deeper imaging over a reasonable portion of the initial field while still providing a useful increase to the survey area. This process would then continue over days, weeks, or months to build up a large, deep survey region. An Inner Oort Cloud object at 100 AU will move  $\sim 4$  pixels over one 10,000-second exposure, and  $\sim 32$  pixels over the course of one day, and would therefore be the easiest to detect. More distant objects at 1000 AU will only move 1 pixel over the course of a day, so varying the amount of time that different portions of the survey field are re-imaged would result in detection of objects from 100 to 1000 AU. The imaging depth of the LSST is not adequate for detection of Inner Oort Cloud objects, so this investigation is only possible with WFIRST. Additionally, the large field of view of WFIRST would contribute to a larger survey area in a shorter amount of time compared to any other ground- or space-based telescope facilities.



**Figure 11:** V magnitude as a function of heliocentric distance for Inner Oort Cloud objects of different diameters. The geometric albedo of these objects is assumed to be 0.04, comparable to long-period comets. The colored curves correspond to different Inner Oort Cloud object diameters, with labels on the right side of the plot. The dashed line marks the V magnitude limit (32.67) for detection in a single 10,000-second exposure through the W149 filter.

## 4.4. Occultation science

### 4.4.1. Targeted occultations

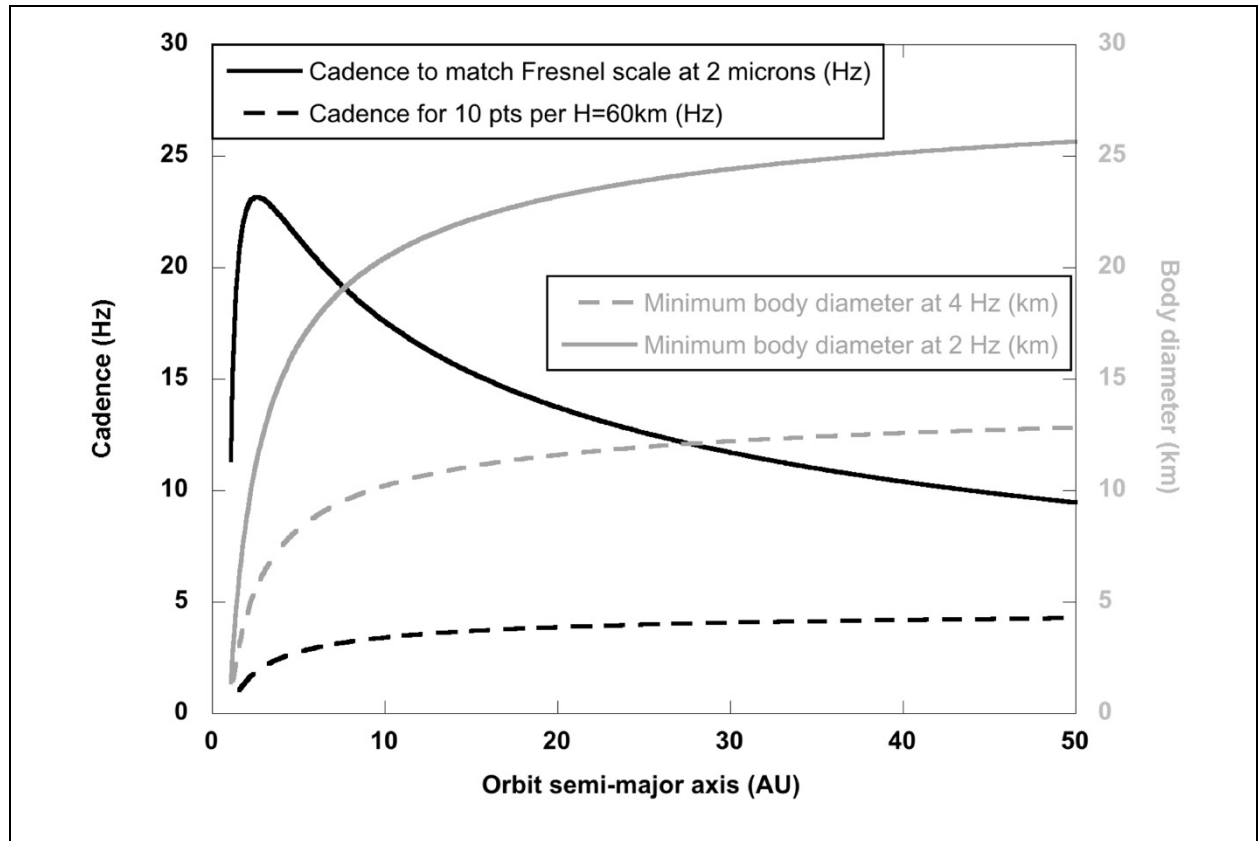
Occultations of a background star by a solar system object are sources of a variety of important information for the determination of sizes, albedos, and shapes of main belt asteroids, Jupiter Trojans, Centaurs, and KBOs (e.g., Millis et al., 1987; Sicardy et al., 2011; Buie et al., 2015; Santos-Sanz et al., 2016; Dias-Oliveira et al., 2017); the detection of ring systems around Uranus and the Centaur Chariklo (Elliot et al., 1977; Braga-Ribas et al., 2014); the detection and study of Pluto's atmosphere (e.g., Elliot et al., 2007); and the study of planetary atmospheres (e.g., Elliot and Olkin, 1996).

Occultation events are rare and sometimes difficult to predict depending on the quality of the solar system target's orbital solution. Expanding coverage beyond the surface of the Earth increases the chances that a particular event will be observable. With its orbital location around the Earth-Sun L2 point, WFIRST will be in position to observe occultations that will not be visible from Earth or from other spacecraft. Due to their slower apparent rates of motion, Centaurs and KBOs will be the primary targets; under the right conditions, WFIRST will be able to observe occultations by faster-moving main belt asteroids and Jupiter Trojans.

In order to achieve the proper imaging cadence ( $\geq 2$  Hz, with  $\sim 25$  Hz ideal for faster-moving targets), a small subarray must be available in the larger field of view for faster readout times. The

maximum readout time required is 0.5 second, with a desired readout time of 0.04 second. The readout time for individual WFIRST detectors is 2.7 seconds, and the guide boxes are anticipated to be  $16 \times 16$  pixels. The readout cadence of this guide box will be 5.8 Hz, above the minimum required cadence for occultation science.

An occultation observation will consist of an occultation imaging series at  $\sim 5.8$  Hz with minimal or no dead time between images; the desired rate is determined by the sky-plane velocity of the occulting body, ideally to match or exceed the Fresnel scale (Fig. 12). The imaging series is tracked at the sidereal rate, maintaining exact positioning on the occulted star as the occulting body passes through the field. (Non-sidereal tracking is needed for the exceptional case of mutual events when, for example, a KBO satellite passes in front of its primary.) Separate photometry of the star and body is required before and/or after the main occultation event. Occultation durations depend on the size of the occulting body and the sky-plane velocity and can range from 1 second to several hours (for giant planet and ring events).



**Figure 12:** Cadence (black) and body diameter (grey) limits for occultations, as a function of body orbital semi-major axis. The curves in black present the cadence required (solid line) to match the Fresnel scale at  $2 \mu\text{m}$  (dashed line) or to achieve 10 points per 60-km scale height in a hypothetical atmosphere, as a function of distance. Notably, a cadence of 10 Hz is required to match the Fresnel scale for bodies in the outer solar system, such as KBOs. If a body were to have a Pluto-like atmosphere with a scale height of 60 km, a cadence of 5 Hz is always sufficient to achieve 10 points per 60-km scale height, a rule of thumb that allows for sufficient resolution to fit for the temperature structure. The curves in red predict the minimum body size that would be resolved with a minimum of two points across the body, for an observing cadence of 2 Hz

(solid line) and 4 Hz (dashed line). KBOs as small as  $\sim 15$  km can be resolved with the targeted occultation technique on WFIRST, although for bodies this size there will be considerable positional uncertainties in the predictions.

#### *4.4.2. Serendipitous occultations*

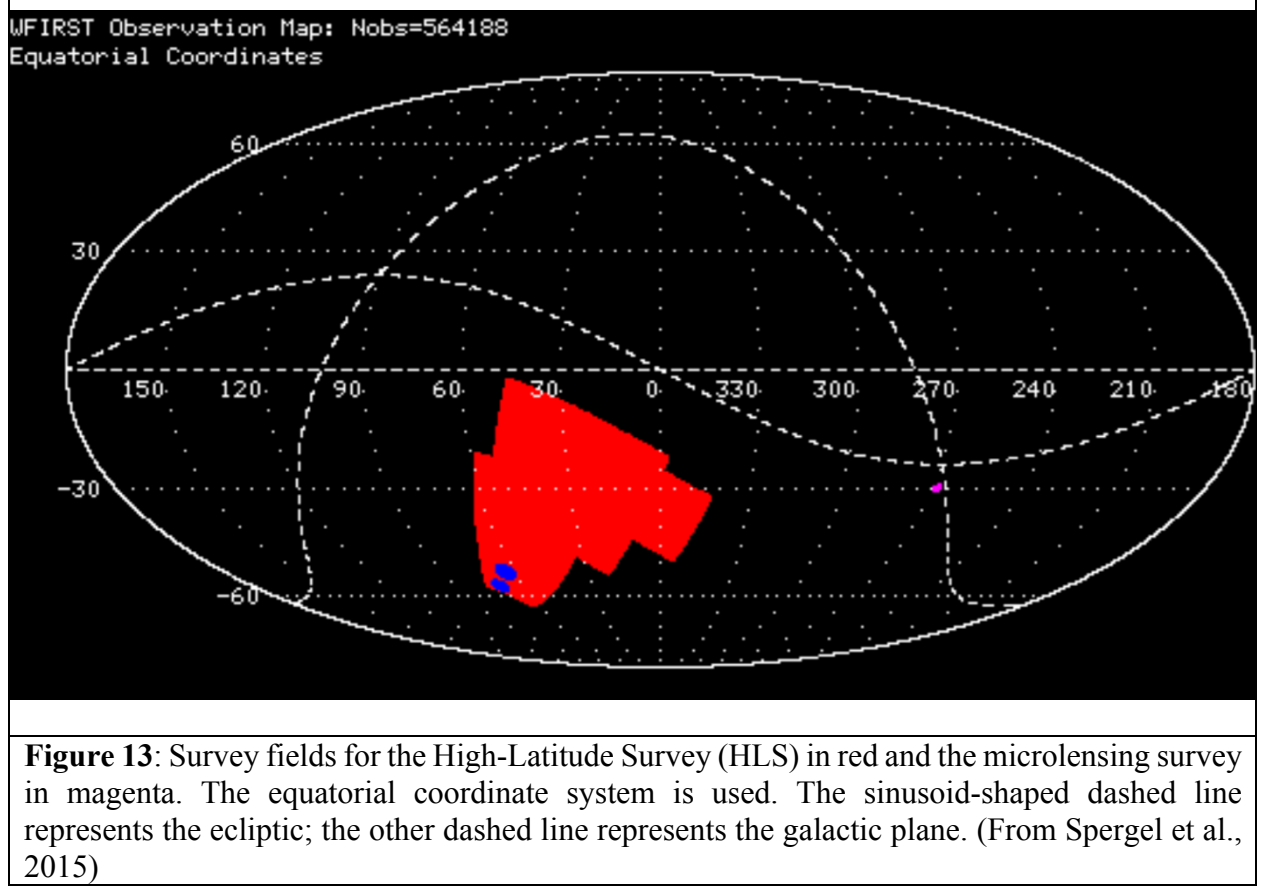
Observing unplanned occultations with WFIRST is also possible and was previously attempted with the Fine Guidance Sensors (FGS) on HST (Schlichting et al., 2009, 2012), in X-rays with the Rossi X-ray Timing Explorer (Chang et al., 2016), and with ground-based observing programs (e.g., Roques et al., 2006; Zhang et al., 2013; Doressoundiram 2016). This method of detecting and characterizing serendipitous occultations is presently the only way to estimate the population of KBOs in the sub-kilometer size range; however, this method does suffer from the random and unrepeatable nature of the observations, and cannot be followed-up. Detections of sub-kilometer sized KBOs were reported from ground-based programs (Roques et al., 2006; Doressoundiram et al., 2016) and two detections were reported in over 30,000 “star hours” from the FGS (Schlichting et al., 2012); two FGS detectors are used for guiding purposes, and each tracks its own guide star, so there are 2 star hours per hour of science observations.

This same process of analyzing guide star images is possible with WFIRST for the WFI and IFC modes, though at a lower cadence than the HST FGS (5.86 Hz vs. 40 Hz; Spergel et al., 2015). However, this cadence is above the 2 Hz threshold and is sufficient for identifying serendipitous occultations by KBOs and other distant solar system objects. In fact, WFIRST should provide an even better opportunity to identify serendipitous occultations than HST because each of the 18 detectors in the WFI field of view can track its own guide star (Nelan et al., 2016). Thus, up to 18 hours of star time per hour of science observations will be possible with WFIRST. Guiding will occur during the majority of the surveys and GO observations, resulting in a very large data set over WFIRST’s mission lifetime for the potential detection of serendipitous occultations.

### **5. Solar system science: Guest Investigator (GI) program**

The Guest Investigator (GI) program will provide funding for analysis of data from the WFIRST astrophysics surveys. Like the GO program, funding through the GI program will be a competitive process. In this section, we discuss the design of the astrophysics surveys and how they could be used for solar system science, using detection and study of new KBOs as an example. This is by no means an exhaustive list of possible investigations, as detection and study of main belt asteroids, Trojan asteroids, and comets are also likely to result from the data obtained with the astrophysics surveys. Other interesting minor bodies such as active asteroids, extrasolar asteroids, Manx comets, and Inner Oort Cloud objects may also be detected during these astrophysics surveys. Members of previously unidentified classes of minor bodies may also be characterized.





**Figure 13:** Survey fields for the High-Latitude Survey (HLS) in red and the microlensing survey in magenta. The equatorial coordinate system is used. The sinusoid-shaped dashed line represents the ecliptic; the other dashed line represents the galactic plane. (From Spergel et al., 2015)

### 5.1. High-Latitude Survey (HLS)

WFIRST's High-Latitude Survey (HLS) will include observations of minor bodies that serendipitously fall within the  $0.28 \text{ deg}^2$  FOV. The proposed  $\sim 2200 \text{ deg}^2$  patrol field (Fig. 13) for the four-filter (Y106, J129, H158, F184) HLS will observe KBOs on inclined, dynamically excited orbits. (This survey could also be used to search for a distant giant planet, as proposed by Batygin and Brown (2016), if it exists and is not found prior to the launch of WFIRST in 2025/2026.) The multi-band WFI photometry will measure the surface composition of Centaurs and KBOs, important for understanding their formation history in the early planetesimal disk and later migration under the gravitational influence of Neptune to their present orbits. The presence of KBOs in WFI imaging is strongly dependent on where WFI images on the sky. KBOs have a complex and finely structured population distribution, with the majority of the population in low-inclination, low-eccentricity orbits, placing them near the ecliptic; the sky density of KBOs decreases rapidly further from the ecliptic. These KBOs likely formed closer to the Sun and have been emplaced on their present orbits by Neptune's migration (e.g., Gomes, 2003), so their composition and dynamics are particularly useful probes of planetary formation and migration history. By the time of WFIRST, the KBO survey efforts of the Dark Energy Survey (using the DECam instrument at the Cerro Tololo Inter-American Observatory), followed by the LSST, will provide a comprehensive catalogue of all  $r < 24.5$  KBOs in this region of sky in Sloan *griz*. The serendipitous WFI imaging will therefore augment the spectral photometry for known KBOs, which will have well-determined orbits with small sky uncertainties within the FOV. Current

estimates for the size of the high-latitude KBO population are exceptionally uncertain: observations of a few hundred KBOs to  $r \sim 25$  is plausible (Sheppard and Trujillo, 2016; Petit et al., 2017). WFIRST will reach  $r \sim 27$  with each set of exposures in a particular filter during the HLS survey (Spergel et al., 2015).

Serendipitous discovery of new KBOs is very likely based on the observing strategy of the HLS. The strategy, as currently designed, is to observe  $\sim 9$  square degrees through one filter, switch filters, and cover the same area again until the same area has been observed through all 4 filters. The exposure length for each filter at each dither position (of which there will be 4 for each pointing) will be 174 seconds. The full  $\sim 9$  square degree area will take  $\sim 5.4$  hours to cover in each filter (slightly longer for the J129 filter due to one additional dither), and approximately a day for that area to be covered through all 4 filters. If we conservatively define “detection” of a moving target as a shift in the centroid position by one WFI pixel ( $\sim 0.11''$ ), objects out to heliocentric distances of  $\sim 17$  AU could be detected between 174-second exposures and out to  $\sim 100$  AU in only  $\sim 45$  minutes. Assuming sufficient brightness in each filter, motion of all solar system objects will be detectable with the 1-day cadence of the HLS; these detections will also be more robust than provided by a 1-pixel shift in the centroid position. WFIRST will return to the same patch of sky every  $\sim 0.5$  years and execute the same strategy at a different roll angle. The return visits could eventually allow mining of moving target discoveries from the transient, non-stationary catalogs (e.g., Larsen et al., 2007; Brown et al., 2015; Gerdes et al., 2017).

The compositional classes of KBOs are only beginning to be understood. KBOs have a steep size distribution and orbit at large heliocentric distances, making most of them small and faint, even for space telescopes. A detailed examination of the population in the proposed WFI bandpasses with multi-band photometry will provide substantial new compositional information. The WFIRST wavelength regions are barely explored for the majority of KBO populations. Ground-based observations require exorbitant amounts of time to provide sufficient SNR to investigate compositional variation. Whether these minor planets are detectable in the observed WFI bandpass will depend on their albedo, diameter, and distance from the Sun. A strong bias will apply to favoring detections at orbital perihelion. KBOs exhibit a range of colors from solar to substantially redder-than-solar (§4.3.6). The proposed WFI filter range covers the ice and tholin-related spectral features that have previously been detected on the larger KBOs and Triton, as well as features indicative of silicates, which have yet to be confirmed on small objects in the KBO population. Thus, detection of new minor bodies with the HLS could probe an interesting subset of the color phase space of the  $< 150$  km diameter KBO population, but it is likely to be challenging to map to dynamical populations and thus composition and migration history unless time is invested in a GO/ToO program to obtain better-quality orbits for these faint KBOs.

## 5.2. Microlensing survey

The WFIRST microlensing survey is designed to detect light curve variations due to a host star passing in front of its planet. This is an effective way to detect planets at further distances from their host stars, and complements the transit method, which is useful for observing planets at smaller orbital distances. This survey will cover 7-8 contiguous WFI fields ( $1.96$ - $2.24$  deg<sup>2</sup>) at quadrature near the galactic bulge between  $265^\circ$  to  $267^\circ$  in RA and  $-30^\circ$  to  $-26^\circ$  in declination (Fig. 13). These 7-8 fields will be observed during 6 non-consecutive 72-day campaigns over the 6-year WFIRST nominal mission. WFIRST will cycle through the 7-8 fields for the entirety of the 72-day campaign, with 15 minutes spent on each field. The majority of the observations will be

through the wide band W149 filter (10 52-second exposures plus overheads); every 12 hours the fields will be observed through the Z087 filter (2 290-second exposures plus overheads). This will result in  $\sim 33,000$  epochs through the W149 filter and  $\sim 700$  through the Z087 filter.

This large number of epochs, and even larger number of individual exposures, will enable detection and further study of slower-moving solar system objects, such as KBOs. According to Gould (2014), an unmodified microlensing survey could detect KBOs down to a V magnitude of 30.2; this equates to objects  $\sim 11$  km in diameter, assuming a heliocentric distance of 40 AU and a geometric albedo of 0.04. KBO satellites would be detectable down to a V magnitude of 31.0 ( $\sim 7$  km) due to a smaller search area. Satellites within 10 mas ( $\sim 0.1$  pixel) could be identified around primaries with a maximum V magnitude of 25.0. Detection of these satellites would result in a significant increase in the total number of known KBO binary systems ( $\sim 80$  are currently known) and thus an increase in known system masses. The high imaging cadence would also allow for the construction of rotational light curves for hundreds of KBOs, significantly increasing the number of known rotation periods. In summary, analysis of the images obtained through the WFIRST microlensing survey would contribute in a meaningful way to the statistical study of KBOs, leading to new insights into their formation and evolution.

## **6. WFIRST mission augmentations**

### **6.1. Non-sidereal tracking**

Non-sidereal tracking of moving targets is necessary for all GO investigations discussed in this paper except occultations. Observations of solar system targets made at a sidereal rate would cause streaking of the target, resulting in unusable data for investigations of spatial variability (e.g., the bands and zones of Jupiter), a loss of SNR for brighter minor bodies by adding read noise from additional pixels, and the non-detection of fainter minor bodies due to the distribution of flux over a larger area on the detector. As discussed in §1 and shown in Table 2, a 30 mas/s track rate (the maximum apparent rate of Mars) is adequate for most investigations discussed in this paper. However, about 10% of NEAs and  $>50\%$  of long-period comets (§4.3.7) would be unobservable at this rate. Increasing this rate to 60 mas/s would enable observations of  $>99\%$  of NEAs and would significantly increase the observability of long-period comets, primitive remnants of the formation of the solar system. We understand that such a high track rate may not be achievable, but any increase over the nominal 30 mas/s rate would nonetheless help increase the number of NEAs and long-period comets observable with WFIRST.

### **6.2. K-band filter**

The inclusion of a K ( $\sim 2.0\text{--}2.4\ \mu\text{m}$ ) or Ks ( $\sim 2.0\text{--}2.3\ \mu\text{m}$ ) filter in the WFI filter wheel would result in a wider variety, as well as more comprehensive, solar system investigations. For instance, imaging in the K-band would provide higher contrast on Io between emission from the surface and emission from active volcanic eruptions. A K or Ks filter would also support imaging to different depths within the atmospheres of the giant planets and Titan compared to the currently commissioned filters.

Two different groups of Jupiter Trojans have been identified based on their near-infrared colors, suggesting two different origins (§4.3.4). Only a few dozen Trojans have measured near-infrared colors, but further characterization of these groups and an evaluation of their origins would

not be possible with WFIRST if it lacks K-band filter. WFIRST's large FOV would be ideal for obtaining colors of more Trojans, with the possibility of obtaining measurements for multiple objects in the same pointing. A significant increase to the sample with measured near-infrared colors would only be possible with a K or Ks filter.

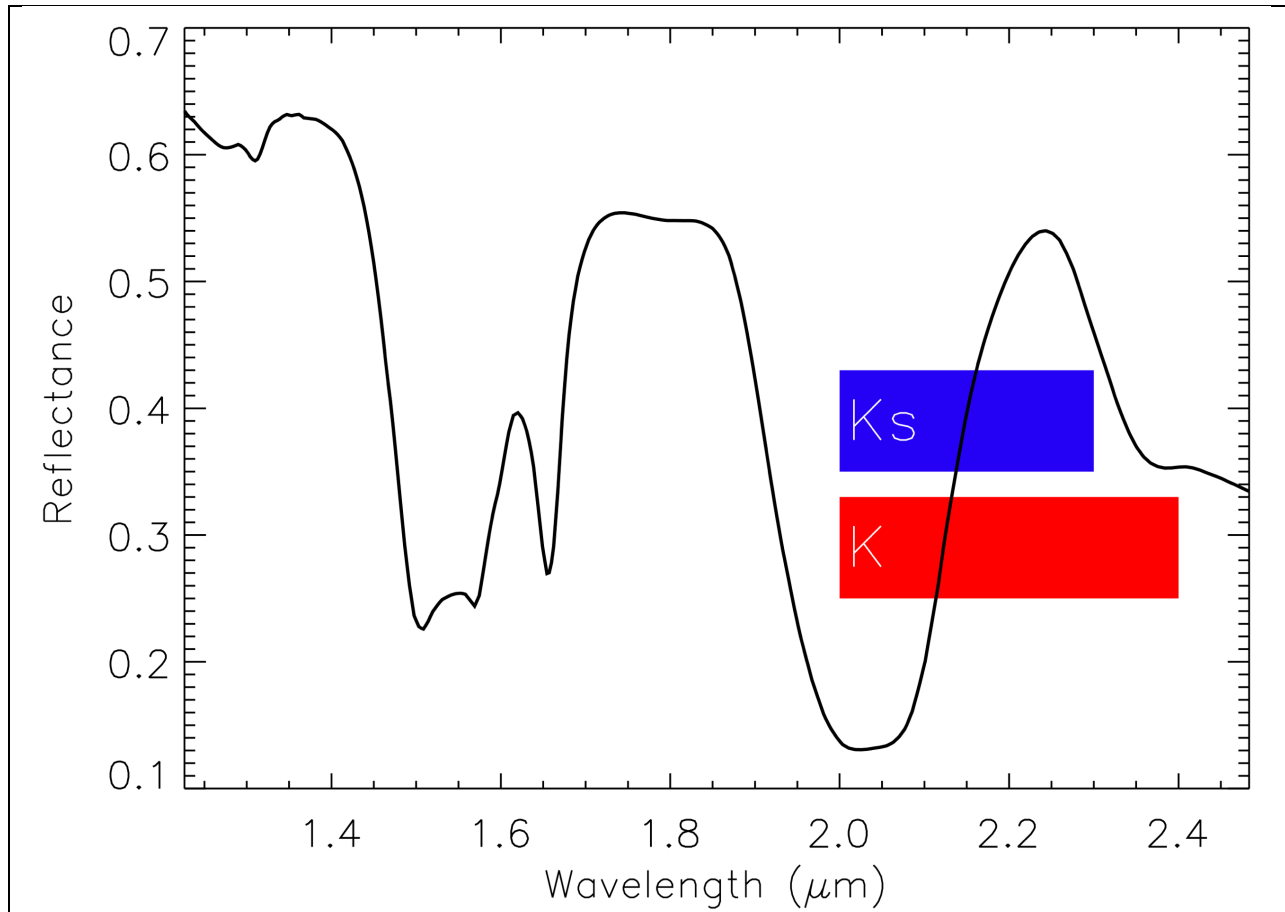
In general, observations through a K-band filter would support more accurate compositional determinations of fainter minor bodies for which spectroscopy is not feasible. The strongest water ice absorption band is centered at  $\sim 2.0 \mu\text{m}$  and presents the best opportunity to detect this ice species, even in smaller quantities on very faint minor bodies, and K-band photometry would provide a more definitive identification than H-band photometry (Fig. 14). The same is true for detection of pyroxene on asteroids (Fig. 8). Extending photometric measurements to these longer wavelengths would in turn extend the range of near-infrared spectral photometry. Comparison of general spectral shapes provides a useful indication of relative spectral properties between bodies. The wider the wavelength range, the more useful the comparison, since an ice or mineral present on one body but not another will be evident in the spectral shape. The K-band is an especially useful indicator due to strong absorption features of many potential surface components, including water ice, methane, pyroxene, and methanol. K-band photometry could therefore be the decisive measurement for determining whether or not two bodies have similar surface compositions.

Table 6 presents the limiting AB magnitudes and sensitivities for 5 different K-band filter options. These numbers were calculated for a spacecraft operating temperature of 260 K. The aperture for the extended sources is circular with a half-light radius of  $0.3''$ . Comparison of the numbers in the third column of Table 6 to Table 3 and the fifth column of Table 6 to Table 4 shows that any of the K-band filter options could be useful for observations of objects throughout the solar system. Any of these filters would be especially useful for extended sources, since extended sources in the solar system tend to be very bright compared to point sources; very high SNRs will be achievable on the giant planets, their large satellites, and bright main belt asteroids.

The solar system community will be able to make use of a visible band filter if that is chosen instead of a K-band filter. (The most important WFIRST capability for solar system observations is moving target tracking, discussed in §6.1.) Such observations with a visible band filter would be comparable to those with HST and include searching for and characterizing satellite orbits around minor bodies due to higher flux in the visible (e.g., Hestroffer et al., 2002; Weaver et al., 2006; Grundy et al., 2015), atmospheric mapping on Jupiter (e.g., Simon et al., 2015), and the study of active asteroids (e.g., Agrawal et al., 2016), to name a few potential investigations.

**Table 6. Estimated K-filter sensitivities**

<b>Wavelength range (<math>\mu\text{m}</math>)</b>	<b>AB mag (extend. source, 3600s, <math>5\sigma</math>)</b>	<b>Surface brightness (<math>\text{Jy}/\square''</math>)</b>	<b>AB mag (pt. source, 3600s, <math>5\sigma</math>)</b>	<b>Flux density (mJy)</b>
2.00-2.20	25.086	$1.19 \times 10^{-6}$	26.082	0.00013
2.00-2.25	25.027	$1.25 \times 10^{-6}$	26.019	0.00014
2.00-2.30	24.935	$1.36 \times 10^{-6}$	25.922	0.00016
2.00-2.35	24.829	$1.50 \times 10^{-6}$	25.812	0.00017
2.00-2.40	24.710	$1.68 \times 10^{-6}$	25.689	0.00019



**Figure 14:** Near-infrared spectrum of crystalline water ice from Grundy and Schmitt (1998). Only a handful of spectra of minor bodies and satellites in the outer solar system exhibit strong water ice absorption features. It is more common for the spectra of these objects, if water ice is present, to show a broad, shallow absorption feature at 2.0  $\mu\text{m}$ , and very little detectable absorption at shorter wavelengths (e.g., Brown, 2000; Barkume et al., 2008). Without a K or Ks filter, constraining the presence of water ice on small outer solar system bodies with WFIRST will not be possible.

### 6.3. Parallel observations

The ability to propose for parallel observations through the GO program would benefit efforts for serendipitous detection of minor bodies. Specifically, use of the WFI during fixed target observations with the IFC would provide additional images over the 0.28 deg<sup>2</sup> WFIRST FOV for the detection of moving targets. Exposures of a few minutes during especially long exposures on the same fixed target would enable detection of distant minor bodies. Faster readout could be used for asteroids and NEAs, assuming no data volume issues.

### 6.4. Target of opportunity (ToO) programs

ToO programs are standard at many observatories, both ground- and space-based, and we would like to see them made available for WFIRST. Quick follow-up observations (within 1 week,

with faster turnaround for faster-moving objects) of newly discovered objects reported by WFIRST, LSST, and other facilities would enable orbit calculations and the initial study of physical properties. Such objects would include NEAs, comets, main belt comets, Trojans asteroids, Centaurs, KBOs, and extrasolar asteroids on extremely hyperbolic orbits; follow-up of NEAs would require a fast turnaround time of up to two days, where KBOs could be followed-up a week later. Without this quick follow-up, many of these objects would soon become lost. ToO programs would also be useful for triggering observations of highly time-variable events, such as cometary activity (a few days), volcanic eruptions on Io (a few days), storms in giant planet atmospheres (a few days), and for occultations that may be uncertain at the time of proposal submission (~2-4 weeks). It is unlikely that ToO activations could occur during the microlensing survey, but we request that they be able to interrupt any of the other three astrophysics surveys (the HLS imaging, HLS spectroscopy, and supernova surveys).

## **6.5. Large programs**

Targeted survey programs would benefit from the availability of a handful of large programs during each cycle. Such programs would enable targeted surveys in the vicinity of the ecliptic for detection of asteroids, Trojans, Centaurs, KBOs, and comets. Coverage of a few contiguous WFI fields with a cadence of a few hours and a duration of a few weeks could probe very deep in a less-crowded field than the one covered by the microlensing survey. Such large programs are currently offered by HST and the Gemini Observatory, and are planned for JWST as early as Cycle 1.

## **7. Community actions**

We encourage the solar system community to continue to follow developments for the WFIRST mission. Some aspects of the mission are still uncertain, including which filters will ultimately be included in the filter wheel and if the IFC will be included in the final design. Continued efforts to identify innovative solar system programs are also encouraged so that the best science can be performed starting as early as the first cycle. The opportunities presented by WFIRST are unique and exciting, and only an informed solar system science community will be able to make the most of them.

## **Acknowledgements**

The authors would like to thank Jeff Kruk for his comments and clarifications, as well as Ed Nelan and Jason Kalirai for their advice. WFIRST is a NASA Astrophysics Science Division joint project of the Goddard Space Flight Center, the Jet Propulsion Laboratory, the California Institute of Technology's Infrared Processing and Analysis Center, and the Space Telescope Science Institute. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work made use of the Minor Planet & Comet Ephemeris Service (IAU Minor Planet Center). M. T. Bannister appreciates support from the UK STFC grant ST/L000709/1.

## **References**

- Agarwal, J., et al., 2016. Hubble and Keck telescope observations of active asteroid 288P/300163 (2006 VW139). *AJ* 151, 12.
- Agnor, C.B., Hamilton, D.P., 2006. Neptune's capture of its moon Triton in a binary-planet gravitational encounter. *Nature* 441, 192-194.
- Alexandersen, M., et al., 2013. A Uranian Trojan and the frequency of temporary giant-planet co-orbitals. *Science* 341, 994-997.
- Alí-Lagoa, V., et al., 2016. Differences between the Pallas collisional family and similarly sized B-type asteroids. *A&A* 591, A14.
- Barkume, K.M., et al., 2008. Near-infrared spectra of Centaurs and Kuiper Belt Objects. *AJ* 135, 55-67.
- Batygin, K., Brown, M.E., 2016. Evidence for a distant giant planet in the solar system. *AJ* 151, 22.
- Bauer, J.M., et al., 2010. Direct detection of seasonal changes on Triton with Hubble Space Telescope. *ApJL* 723, L49-L52.
- Bauer, J.M., et al., 2012. WISE/NEOWISE observations of active bodies in the Main Belt. *ApJ* 747, 49.
- Bauer, J.M., et al., 2013. Centaurs and Scattered Disk Objects in the thermal infrared: Analysis of *WISE/NEOWISE* observations. *ApJ* 773, 22.
- Bauer, J.M., et al., 2015. The NEOWISE-discovered comet population and the CO+CO<sub>2</sub> production rates. *ApJ* 814, 85.
- Bauer, J.M., et al., 2017. Debiasing the NEOWISE cryogenic mission comet population. *AJ* 154, 53.
- Bellucci, A., et al., 2009. Titan solar occultation observed by Cassini/VIMS: Gas absorption and constraints on aerosol composition. *Icarus* 201, 198-216.
- Belton, M.J.S., et al., 1996a. Galileo's encounter with 243 Ida: An overview of the imaging experiment. *Icarus* 120, 1-19.
- Belton, M.J.S., et al., 1996b. The discovery and orbit of 1993 (243) 1 Dactyl. *Icarus* 120, 185-199.
- Beneccchi, S.D., et al., 2010. (47171) 1999 TC<sub>36</sub>, a transneptunian triple. *Icarus* 207, 978-991.

- Bodewits, D., et al., 2007. Spectral analysis of the Chandra comet survey. *A&A* 469, 1183-1195.
- Bodewits, D., et al., 2011. Collisional excavation of asteroid (596) Scheila. *ApJL* 733, L3.
- Bodewits, D., et al., 2015. The pre-perihelion activity of dynamically new comet C/2013 A1 (Siding Spring) and its close encounter with Mars. *ApJL* 802, L6.
- Braga-Ribas, F., et al., 2014. A ring system detected around the Centaur (10199) Chariklo. *Nature* 508, 72-75.
- Brasser, R., et al., 2012. An Oort Cloud origin for the high-inclination, high-perihelion Centaurs. *MNRAS* 420, 3396-3402.
- Brown, M.E., 2000. Near-infrared spectroscopy of Centaurs and irregular satellites. *AJ* 119, 977-983.
- Brown, M.E., et al., 2011. A hypothesis for the color diversity of the Kuiper Belt. *ApJL* 739, L60.
- Brown, M.E., et al., 2015. A serendipitous all sky survey for bright objects in the outer Solar System. *AJ* 149, 69.
- Buie, M.W., et al., 2010. Pluto and Charon with the Hubble Space Telescope. II. Resolving changes on Pluto's surface and a map for Charon. *AJ* 139, 1128-1143.
- Buie, M.W., et al., 2015. Size and shape from stellar occultation observations of the double Jupiter Trojan Patroclus and Menoetius. *AJ* 149, 113.
- Caldwell, J., et al., 1992. Titan: Evidence for seasonal change – A comparison of Hubble Space Telescope and Voyager images. *Icarus* 97, 1-9.
- Chang, H.-K., et al., 2016. Upper limits to the number of Oort Cloud objects based on serendipitous occultation events search in X-rays. *MNRAS* 462, 1952-1960.
- Chen, Y.-T., et al., 2016. Discovery of a new retrograde trans-Neptunian object: Hint of a common orbital plane for low semimajor axis, high-inclination TNOs and Centaurs. *ApJL* 827, L24.
- Christy, J.W., Harrington, R.S., 1978. The satellite of Pluto. *AJ* 83, 1005-1008.
- Clark, R.N., McCord, T.B., 1979. Jupiter and Saturn – Near-infrared spectral albedos. *Icarus* 40, 180-188.
- Clark, R.N., et al., 2010. Detection and mapping of hydrocarbon deposits on Titan. *JGR* 115, E10005.
- Connors, M., et al., 2011. Earth's Trojan asteroid. *Nature* 475, 481-483.



- de Kleer, K., de Pater, I., 2016. Time variability of Io's volcanic activity from near-IR adaptive optics observations on 100 nights in 2013-2015. *Icarus* 280, 378-404.
- de la Fuente Marcos, C., de la Fuente Marcos, R., 2014. Large retrograde Centaurs: Visitors from the Oort Cloud? *Ap&SS* 352, 409-419.
- Dias-Oliveira, A., et al., 2017. Study of the plutino object (208996) 2003 AZ84 from stellar occultations: size, shape and topographic features. *AJ* 154, 22.
- Dones, L., et al., 2015. Origin and evolution of the cometary reservoirs. *Space Sci. Rev.* 197, 191-269.
- Doressoundiram, A., et al., 2016. An exploration of the trans-Neptunian region through stellar occultations and MIOSOTYS. *AAS/Division for Planetary Sciences* 48, #120.09.
- Elliot, J.L., et al., 1977. The rings of Uranus. *Nature* 267, 328-330.
- Elliot, J.L., Olkin, C.B., 1996. Probing planetary atmospheres with stellar occultations. *Ann. Rev. E&PS* 24, 89-124.
- Elliot, J.L., et al., 2007. Changes in Pluto's atmosphere: 1988-2006. *AJ* 134, 1-13.
- Emery, J.P., et al., 2011. Near-infrared spectroscopy of Trojan asteroids: Evidence for two compositional groups. *AJ* 141, 25.
- Farkas-Takács, A., et al., 2017. Properties of the irregular satellite system around Uranus inferred from K2, Herschel, and Spitzer observations. *arXiv:1706.06837*.
- Fernández, Y.R., et al., 2013. Thermal properties, sizes, and size distribution of Jupiter-family cometary nuclei. *Icarus* 226, 1138-1170.
- Fieber-Beyer, S.K., et al., 2011. The Maria asteroid family: Genetic relationships and a plausible source of mesosiderites near the 3:1 Kirkwood Gap. *Icarus* 213, 524-537.
- Fink, U., Larson, H.P., 1979. The infrared spectra of Uranus, Neptune, and Titan from 0.8-2.5 microns. *ApJ* 233, 1021-1040.
- Francis, P.J., 2005. The demographics of long-period comets. *ApJ* 635, 1348-1361.
- French, L.M., et al., 2013. A troop of Trojans: Photometry of 24 Jovian Trojan asteroids. *Bulletin of the Minor Planets Section of the Association of Lunar and Planetary Observers* 40, 198-203.
- Gehrels, N., et al., 2015. Wide-Field InfraRed Survey Telescope (WFIRST) mission and synergies with LISA and LIGO-Virgo. *Journal of Phys.: Conf. Series* 610, 012007.

- Gerdes, D.W., et al., 2017. Discovery and physical characterization of a large scattered disk object at 92 au. *ApJL* 839, L15.
- Gladman, B., et al., 2002. Evidence for an extended scattered disk. *Icarus* 157, 269-279.
- Gomes, R.S., 2003. The origin of the Kuiper Belt high-inclination population. *Icarus* 161, 404-418.
- Gould, A., 2014. WFIRST ultra-precise astrometry I: Kuiper Belt Objects. *Journal of the Korean Astronomical Society* 47, 279-291.
- Grav, T., et al., 2003. Photometric survey of the irregular satellites. *Icarus* 166, 33-45.
- Grav, T., Holman, M.J., 2004. Near-infrared photometry of the irregular satellites of Jupiter and Saturn. *ApJ* 605, L141-L144.
- Grav, T., et al., 2012. WISE/NEOWISE observations of the Hilda population: Preliminary results. *ApJ* 744, 197.
- Griffith, C.A., et al., 2009. Characterization of clouds in Titan's tropical atmosphere. *ApJL* 702, L105-L109.
- Grundy, W.M., Schmitt, B., 1998. The temperature-dependent near-infrared absorption spectrum of hexagonal H<sub>2</sub>O ice. *JGR* 103, 25809-25822.
- Grundy, W.M., et al., 2014. Near-infrared spectral monitoring of Pluto's ices II: Recent decline of CO and N<sub>2</sub> ice absorptions. *Icarus* 235, 220-224.
- Grundy, W.M., et al., 2015. The mutual mass, orbit, and density of the large transneptunian binary system Varda and Ilmarë. *Icarus* 257, 130-138.
- Hammel, H.B., et al., 2001. New measurements of the winds of Uranus. *Icarus* 153, 229-235.
- Hardersen, P.S., et al., 2014. More chips off of asteroid (4) Vesta: Characterization of eight Vestoids and their HED meteorite analogs. *Icarus* 242, 269-282.
- Hestroffer, D., et al., 2002. Asteroids observations with the Hubble Space Telescope. I. Observing strategy, and data analysis and modeling process. *A&A* 391, 1123-1132.
- Hills, J.G., 1981. Comet showers and the steady-state infall of comets from the Oort Cloud. *AJ* 86, 1730-1740.
- Holler, B.J., et al., 2016. On the surface compositions of Triton's southern latitudes. *Icarus* 267, 255-266.

- Horner, J., et al., 2004. Simulations of the population of Centaurs – I. The bulk statistics. *MNRAS* 354, 798-810.
- Hsieh, H.H., Jewitt, D., 2006. A population of comets in the Main Asteroid Belt. *Science* 312, 561-563.
- Hsieh, H.H., et al., 2012. Optical and dynamical characterization of comet-like main-belt asteroid (596) Scheila. *ApJ* 744, 9.
- Hsieh, H.H., et al., 2015. The main-belt comets: The Pan-STARRS1 perspective. *Icarus* 248, 289-312.
- Jewitt, D., 2009. The active Centaurs. *AJ* 137, 4296-4312.
- Jewitt, D., et al., 2015. The active asteroids. In: Michel, P., DeMeo, F.E., Bottke, W.F. (Eds.), *Asteroids IV*. University of Arizona Press, Tucson, pp. 221-241.
- Kaib, N.A., Quinn, T., 2009. Reassessing the source of long-period comets. *Science* 325, 1234-1236.
- Karkoschka, E., 1994. Spectrophotometry of the jovian planets and Titan at 300- to 1000-nm wavelength: The methane spectrum. *Icarus* 111, 174-192.
- Karkoschka, E., 2015. Uranus' southern circulation revealed by Voyager 2: Unique characteristics. *Icarus* 250, 294-307.
- Kelley, M.S.P., et al., 2016. Cometary science with the James Webb Space Telescope. *PASP* 128, 018009.
- Kelley, M.S.P., et al., 2017. Mid-infrared spectra of comet nuclei. *Icarus* 284, 344-358.
- Kiss, C., et al., 2017. Discovery of a satellite of the large trans-Neptunian object (225088) 2007 OR<sub>10</sub>. *ApJL* 838, L1.
- Lamy, P.L., et al., 2004. The sizes, shapes, albedos, and colors of cometary nuclei. In: Festou, M.C., Keller, H.U., Weaver, H.A. (Eds.), *Comets II*. University of Arizona Press, Tucson, pp. 223-264.
- Larsen, J.A., et al., 2007. The search for distant objects in the Solar System using Spacewatch. *AJ* 133, 1247-1270.
- Lellouch, E., et al., 2013. "TNOs are Cool": A survey of the trans-Neptunian region. IX. Thermal properties of Kuiper Belt objects and Centaurs from combined Herschel and Spitzer observations. *A&A* 557, A60.

- Levison, H.F., et al., 2010. Capture of the Sun's Oort Cloud from stars in its birth cluster. *Science* 329, 187-190.
- Levison, H.F., et al., 2017. Lucy: Surveying the diversity of the Trojan asteroids: The fossils of planet formation. 48<sup>th</sup> Lunar and Planetary Science Conference, #2025.
- Li, C., Ingersoll, A.P., 2015. Moist convection in hydrogen atmospheres and the frequency of Saturn's giant storms. *Nature Geoscience* 8, 398-403.
- Lisse, C.M., et al., 2006. Spitzer spectral observations of the Deep Impact ejecta. *Science* 313, 635-640.
- Lisse, C.M., et al., 2017. The puzzling detection of x-rays from Pluto and Charon. *Icarus* 287, 103-109.
- LSST Science Collaboration, 2009. LSST Science Book, Version 2.0. arXiv:0912.0201.
- Mainzer, A., et al., 2011. Preliminary results from NEOWISE: An enhancement to the Wide-field Infrared Survey Explorer for Solar System science. *ApJ* 731, 53.
- Mainzer, A., et al., 2014. Initial performance of the NEOWISE reactivation mission. *ApJ* 792, 30.
- Mainzer, A.K., et al., 2015. The Near-Earth Object Camera: A next-generation minor planet survey. *AAS/Division for Planetary Sciences* 47, #308.01.
- Masiero, J.R., et al., 2011. Main belt asteroids with WISE/NEOWISE. I. Preliminary albedos and diameters. *ApJ* 741, 68.
- McCord, T.B., et al., 1999. Hydrated salt minerals on Europa's surface from the Galileo near-infrared mapping spectrometer (NIMS) investigation. *JGR* 104, 11827-11852.
- Meech, K.J., Svoreň, J., 2004. Using cometary activity to trace the physical and chemical evolution of cometary nuclei. In: Festou, M.C., Keller, H.U., Weaver, H.A. (Eds.), *Comets II*. University of Arizona Press, Tucson, pp. 317-335.
- Miglorini, A., et al., 2017. Spectral characterization of V-type asteroids outside the Vesta family. *MNRAS* 464, 1718-1726.
- Milam, S.N., et al., 2016. The James Webb Space Telescope's plan for operations and instrument capabilities for observations in the Solar System. *PASP* 128, 018001.
- Milani, A., et al., 2014. Asteroid families classification: Exploiting very large datasets. *Icarus* 239, 46-73.
- Millis, R.L., et al., 1987. The size, shape, density, and albedo of Ceres from its occultation of BD+8°471. *Icarus* 72, 507-518.

- Molnár, L., et al., 2017. Main-belt asteroids in the K2 Uranus field. arXiv:1706.06056.
- Müller, T.G., et al., 2009. TNOs are Cool: A survey of the transneptunian region. *EM&P* 105, 209-219.
- Nelan, E., et al., 2016. Guide star availability for the WFIRST auxiliary FGS using GSC2.3. WFIRST-STScI-TR1604.
- Nesvorný, D., et al., 2004. Collisional origin of families of irregular satellites. *AJ* 127, 1768-1783.
- Nesvorný, D., et al., 2015. Identification and dynamical properties of asteroid families. In: Michel, P., DeMeo, F.E., Bottke, W.F. (Eds.), *Asteroids IV*. University of Arizona Press, Tucson, pp. 297-321.
- Nicholson, P.D., et al., 2008. Irregular satellites of the giant planets. In: Barucci, M.A., Boehnhardt, H., Cruikshank, D.P., Morbidelli, A. (Eds.), *The Solar System Beyond Neptune*. University of Arizona Press, Tucson, pp. 161-179.
- Noll, K.S., et al., 2008. Binaries in the Kuiper Belt. In: Barucci, M.A., Boehnhardt, H., Cruikshank, D.P., Morbidelli, A. (Eds.), *The Solar System Beyond Neptune*. University of Arizona Press, Tucson, pp. 345-363.
- Oort, J.H., 1950. The structure of the cloud of comets surrounding the Solar System and a hypothesis concerning its origin. *Bulletin of the Astronomical Institutes of the Netherlands* 11, 91-110.
- Ootsubo, T., et al., 2010. Detection of parent H<sub>2</sub>O and CO<sub>2</sub> molecules in the 2.5-5  $\mu$ m spectrum of comet C/2007 N3 (Lulin) observed with AKARI. *ApJL* 717, L66-L70.
- Paganini, L., et al., 2013. Ground-based infrared detections of CO in the Centaur-comet 29P/Schwassmann-Wachmann 1 at 6.26 AU from the Sun. *ApJ* 766, 100.
- Pál, A., et al., 2016. Large size and slow rotation of the trans-Neptunian object (225088) 2007 OR<sub>10</sub> discovered from Herschel and K2 observations. *AJ* 151, 117.
- Paolicchi, P., Knežević, Z., 2016. Footprints of the YORP effect in asteroid families. *Icarus* 274, 314-326.
- Pappalardo, R.T., et al., 2015. Science and reconnaissance from the Europa Clipper mission concept: Exploring Europa's habitability. 46<sup>th</sup> Lunar and Planetary Science Conference, #2673.
- Parker, A.H., et al., 2016. Discovery of a Makemakean moon. *ApJL* 825, L9.

- Petit, J.-M., et al., 2017. The Canada-France Ecliptic Plane Survey (CFEPS) – High-latitude component. *AJ* 153, 236.
- Pike, R.E., et al., 2017. Col-OSSOS: z-band photometry reveals three distinct TNO surface types. *AJ* 154, 101.
- Protopapa, S., et al., 2014. Water ice and dust in the innermost coma of comet 103P/Hartley 2. *Icarus* 238, 191-204.
- Rauer, H., et al., 1997. Millimetric and optical observations of Chiron. *P&SS* 45, 799-805.
- Reach, W.T., et al., 2013. Survey of cometary CO<sub>2</sub>, CO, and particulate emissions using the Spitzer Space Telescope. *Icarus* 226, 777-797.
- Reddy, V., et al., 2014. Chelyabinsk meteorite explains unusual spectral properties of Baptistina asteroid family. *Icarus* 237, 116-130.
- Rivkin, A.S., et al., 2007. Composition of the L5 Mars Trojans: Neighbors, not siblings. *Icarus* 192, 434-441.
- Rodriguez, S., et al., 2006. Cassini/VIMS hyperspectral observations of the HUYGENS landing site on Titan. *P&SS* 54, 1510-1523.
- Romon, J., et al., 2001. Photometric and spectroscopic observations of Sycorax, satellite of Uranus. *A&A* 376, 310-315.
- Roques, F., et al., 2006. Exploration of the Kuiper Belt by high-precision photometric stellar occultations: First results. *AJ* 132, 819-822.
- Roth, L., et al., 2014. Transient water vapor at Europa's South pole. *Science* 343, 171-174.
- Ryan, E.L., et al., 2017. Trojan asteroids in the Kepler Campaign 6 field. *AJ* 153, 116.
- Sánchez-Lavega, A., et al., 1991. The Great White Spot and disturbances in Saturn's equatorial atmosphere during 1990. *Nature* 353, 397-401.
- Sánchez-Lavega, A., et al., 2001. The merger of two giant anticyclones in the atmosphere of Jupiter. *Icarus* 149, 491-495.
- Sánchez-Lavega, A., et al., 2012. Ground-based observations of the long-term evolution and death of Saturn's 2010 Great White Spot. *Icarus* 220, 561-576.
- Santos-Sanz, P., et al., 2016. James Webb Space Telescope observations of stellar occultations by Solar System bodies and rings. *PASP* 128, 018011.

- Schlichting, H.E., et al., 2009. A single sub-kilometre Kuiper belt object from a stellar occultation in archival data. *Nature* 462, 895-897.
- Schlichting, H.E., et al., 2012. Measuring the abundance of sub-kilometer-sized Kuiper Belt Objects using stellar occultations. *ApJ* 761, 150.
- Sheppard, S.S., Jewitt, D.C., 2003. An abundant population of small irregular satellites around Jupiter. *Nature* 423, 261-263.
- Sheppard, S.S., 2006. Outer irregular satellites of the planets and their relationship with asteroids, comets and Kuiper Belt objects. In: Daniela, L., Sylvia Ferraz, M., Angel, F.J. (Eds.), *IAU Symposium 229*. Cambridge University Press, Cambridge, pp. 319-334.
- Sheppard, S.S., Trujillo, C.A., 2006. A thick cloud of Neptune Trojans and their colors. *Science* 313, 511-514.
- Sheppard, S.S., Trujillo, C., 2016. New extreme trans-Neptunian objects: Towards a super-Earth in the outer Solar System. *AJ* 152, 221.
- Showalter, M.R., Lissauer, J.J., 2006. The second ring-moon system of Uranus: Discovery and dynamics. *Science* 311, 973-977.
- Showalter, M.R., et al., 2011. New satellite of (134340) Pluto: S/2011 (134340) 1. *IAU Circ.* 9221, #1.
- Showalter, M.R., et al., 2012. New satellite of (134340) Pluto: S/2012 (134340) 1. *IAU Circ.* 9253, #1.
- Showalter, M.R., et al., 2013. The Neptune system revisited: New results on moons and rings from the Hubble Space Telescope. *AAS/Division for Planetary Sciences* 45, #206.01.
- Showalter, M.R., Hamilton, D.P., 2015. Resonant interactions and chaotic rotation of Pluto's small moons. *Nature* 522, 45-49.
- Sicardy, B., et al., 2011. A Pluto-like radius and a high albedo for the dwarf planet Eris from an occultation. *Nature* 478, 493-496.
- Simon, A.A., et al., 2015. First results from the Hubble OPAL program: Jupiter in 2015. *ApJ* 812, 55.
- Simon, A.A., et al., 2016. Neptune's dynamic atmosphere from Kepler K2 observations: Implications for brown dwarf light curve analyses. *ApJ* 817, 162.
- Smith, B.A., et al., 1986. Voyager 2 in the Uranian system: Imaging science results. *Science* 233, 43-64.

- Sparks, W.B., et al., 2016. Probing for evidence of plumes on Europa with HST/STIS. *ApJ* 829, 121.
- Spencer, J.R., et al., 2015. The successful search for a post-Pluto KBO flyby target for New Horizons using the Hubble Space Telescope. *European Planetary Science Congress 2015*, EPSC2015-417.
- Spergel, D., 2015. Wide-Field InfraRed Survey Telescope – Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report. *arXiv:1503.03757*.
- Spoto, F., et al., 2015. Asteroid family ages. *Icarus* 257, 275-289.
- Sromovsky, L.A., et al., 2003. The nature of Neptune’s increasing brightness: evidence for a seasonal response. *Icarus* 163, 256-261.
- Sromovsky, L.A., et al., 2009. Uranus at equinox: Cloud morphology and dynamics. *Icarus* 203, 265-286.
- Sromovsky, L.A., et al., 2015. High S/N Keck and Gemini AO imaging of Uranus during 2012-2014: New cloud patterns, increasing activity, and improved wind measurements. *Icarus* 258, 192-223.
- Stern, S.A., et al., 2015. The Pluto system: Initial results from its exploration by New Horizons. *Science* 350, aad1815.
- Szabó, G.M., et al., 2012. Evidence for fresh frost layer on the bare nucleus of comet Hale-Bopp at 32 AU distance. *ApJ* 761, 8.
- Szabó, G.M., et al., 2017. The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids. *A&A* 599, A44.
- Tegler, S.C., et al., 2016. Two color populations of Kuiper Belt and Centaur objects and the smaller orbital inclinations of red Centaur objects. *AJ* 152, 210.
- Thomas, C.A., et al., 2011. Space weathering of small Koronis family members. *Icarus* 212, 158-166.
- Trujillo, C.A., Brown, M.E., 2002. A correlation between inclination and color in the Classical Kuiper Belt. *ApJ* 566, L125-L128.
- Turtle, E.P., et al., 2011. Rapid and extensive surface changes near Titan’s equator: Evidence of April showers. *Science* 331, 1414-1417.
- Verbiscer, A.J., et al., 2009. Saturn’s largest ring. *Nature* 461, 1098-1100.
- Veverka, J., et al., 1996. Dactyl: Galileo observations of Ida’s satellite. *Icarus* 120, 200-211.



- Vilenius, E., et al., 2014. “TNOs are Cool”: A survey of the trans-Neptunian region. X. Analysis of classical Kuiper Belt objects from Herschel and Spitzer observations. *A&A* 564, A35.
- Weaver, H.A., et al., 2006. Discovery of two new satellites of Pluto. *Nature* 439, 943-945.
- Wong, I., Brown, M.E., 2016. A hypothesis for the color bimodality of Jupiter Trojans. *AJ* 152, 90.
- Wong, I., Brown, M.E., 2017. The bimodal color distribution of small Kuiper Belt objects. *AJ* 153, 145.
- Yang, B., et al., 2014. Multi-wavelength observations of comet C/2011 L4 (Pan-STARRS). *ApJL* 784, L23.
- Zhang, Z.-W., et al., 2013. The TAOS Project: Results from seven years of survey data. *AJ* 146, 14.